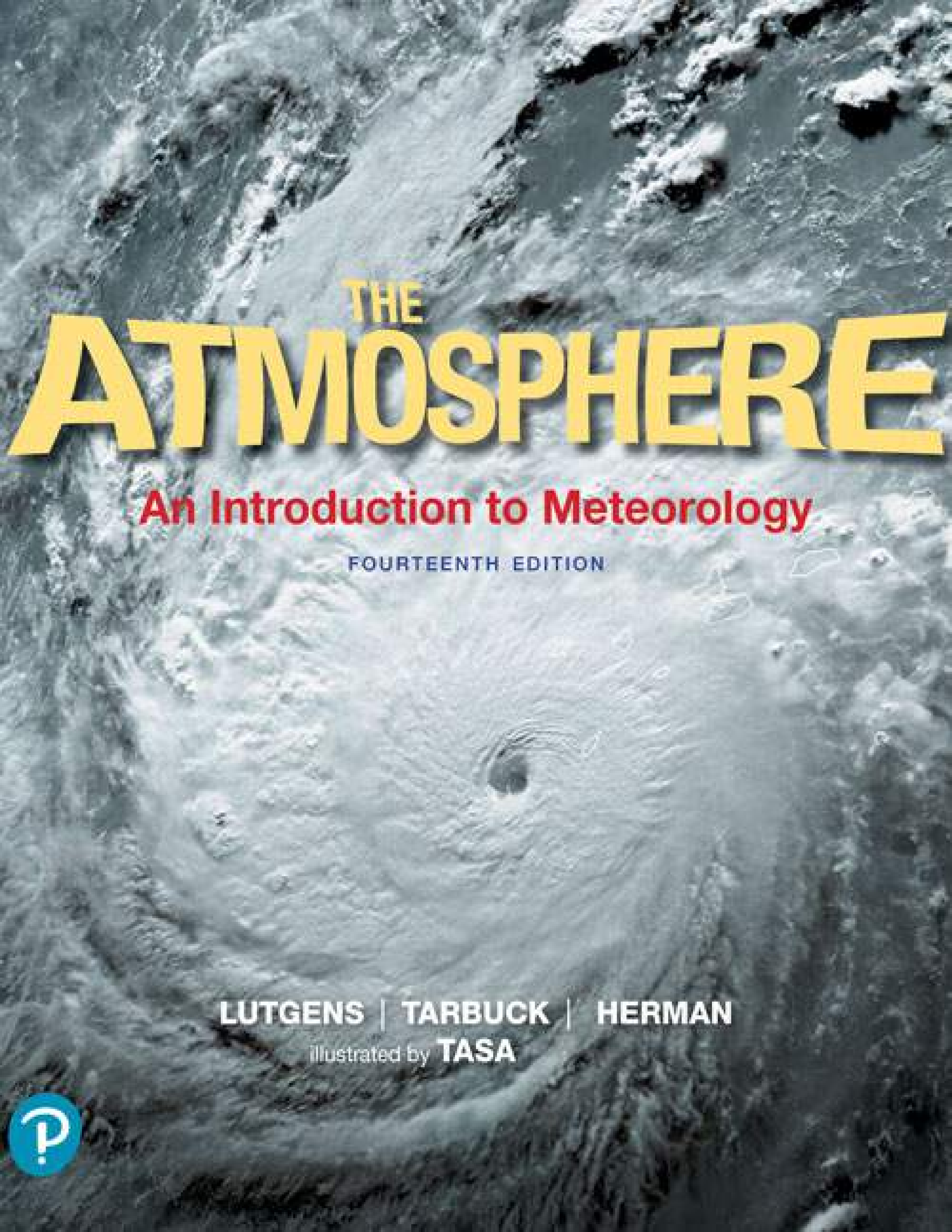


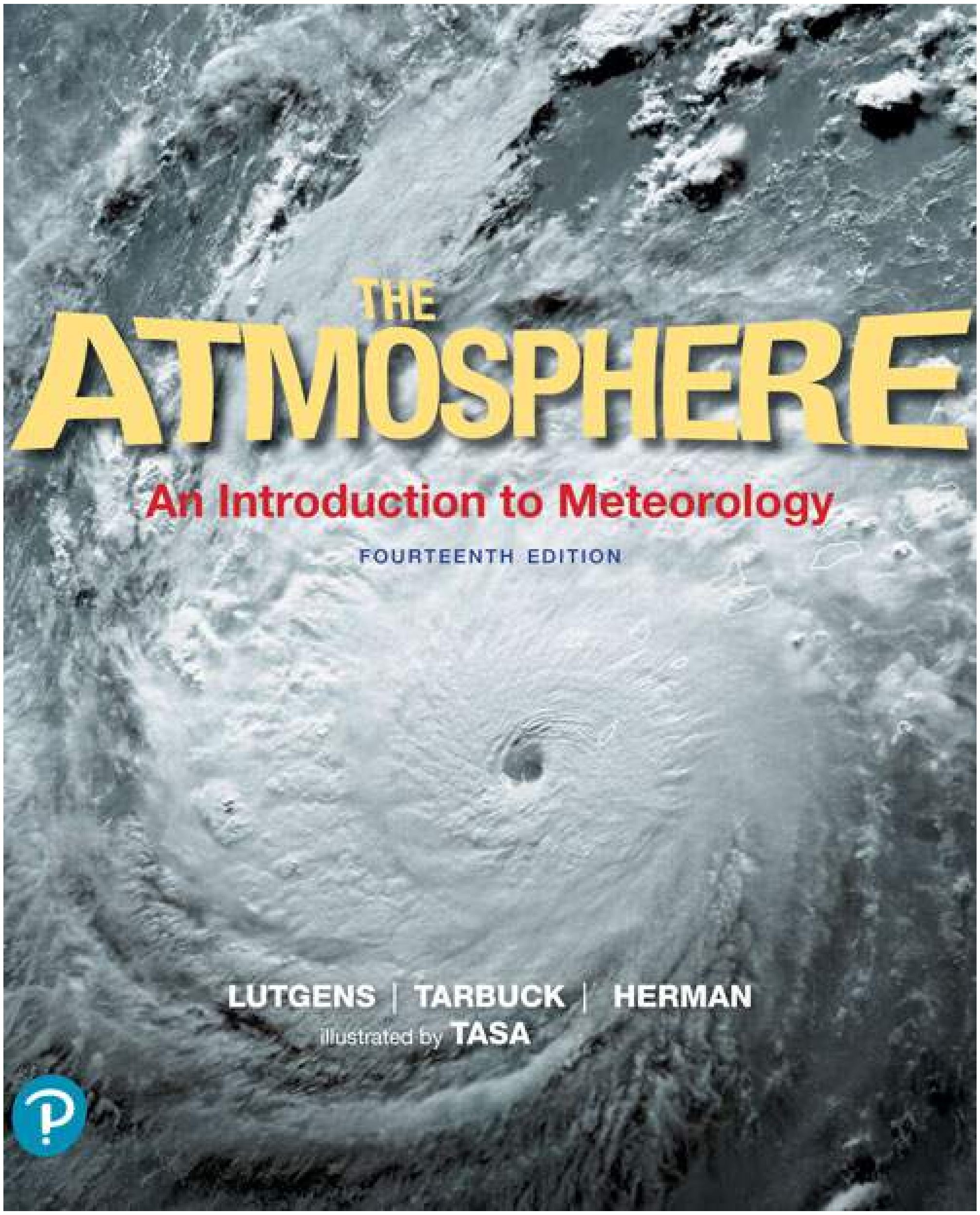
THE ATMOSPHERE

An Introduction to Meteorology

FOURTEENTH EDITION

LUTGENS | TARBUCK | HERMAN

illustrated by TASA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The Atmosphere

An Introduction to Meteorology

Fourteenth Edition

Frederick K. Lutgens

Edward J. Tarbuck

Redina L. Herman

illustrated by Dennis Tasa

Pearson

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Brief Contents

Mastering Meterology Media

Preface

Weather is something we experience firsthand, but often we don't know why things happen the way they do. The fourteenth edition of *The Atmosphere* helps students understand why these things happen. This college-level textbook is a nontechnical survey of weather and the atmosphere, intended for students taking their first, and perhaps only, course in meteorology. Our goal in writing *The Atmosphere* is to help students understand the processes that control our weather and be able to apply this information in their daily lives.

New to This Edition

The fourteenth edition of *The Atmosphere* is streamlined to be more student oriented, with guideposts to a clear learning path from beginning to end of each chapter. We make use of experience gained from many years of teaching introductory weather and climate courses to add more process-oriented descriptions. Some chapters are reorganized and significantly revised to improve the flow of the discussion, and the material is updated based on current meteorology research. Most chapters have been reduced in length without cutting important content. Some of the textbook-wide changes include the following:

- An **improved active learning path** that creates a learning ladder, where each rung brings a deeper mastery of the material:
  - **Focus on Concepts**, appearing at the beginning of each chapter, lists learning objectives (many of which have been revised) to help students get a "lay of the land" before starting the chapter.
  - **Each major section** repeats the learning goal with a single bulleted visual to keep students focused.
  - Key concepts in every section are highlighted using one to two **pull quotes (NEW)** to help students synthesize the section information.
  - **Key terms** are in bold where they are defined in the text.
  - **Concept Checks** are a set of three to four questions placed at the end of each major section to help students test their recall of the main points of the section.
  - **Concepts in Review** tie back to Focus on Concepts (the learning objectives), summarize the main points (many revised) for each section, and now incorporate visual cues for each section to aid with recall and understanding. These reviews bring the learning path full circle for students.

- **Review Questions (NEW)** provide students with an opportunity to test their understanding of the chapter as a whole.
- Requiring a higher level of understanding, the **Give It Some Thought** section challenges students to synthesize concepts and apply this knowledge to answer questions.
- **By the Numbers** (formerly called Problems) requires students to use basic math skills to solve quantitative problems related to key concepts.
- **Beyond the Textbook (NEW)** features one to two links to websites with atmospheric, weather, or climate data (animated maps, tables, diagrams, etc.). Students answer data analysis questions based on actual current conditions or a specific locale. This allows students to see how concepts in the chapter play out in the real world and in real time.

- Updated figures make learning easier by illustrating processes and examples in each chapter. Once again we are privileged to work with Dennis Tasa, whose artistic creations are stunning. There are **129 figures** that are new or substantially revised to help clarify difficult concepts. There are **49 new photographs** of real-world weather situations to keep the textbook current and relevant.
- Weather safety is more fully integrated into the textbook. Every Severe & Hazardous Weather feature now contains **Weather Safety tips (NEW)**. Weather safety tips are also added to the text in several chapters.
- **Mastering Meteorology** delivers engaging, dynamic learning opportunities—focused on course objectives and responsive to each student's progress—that are proven to help students absorb course material and understand difficult concepts.
  - **Integrated Mobile Media with accompanying review questions.** QR links to mobile-enabled *Videos* and *Geoscience Animations* are integrated throughout the chapters, giving students just-in-time access to animations of key physical processes and videos of real-

world case studies and data visualizations. The video selection has been revised and updated. These media are also available in the Study Area of Mastering Meteorology. There are also short quizzes for each video in Mastering Meteorology.

  - **SmartFigures** are brief, narrated video lessons that examine and explain concepts illustrated by key figures within the text. Students access SmartFigures on their mobile devices by scanning Quick Response (QR) codes next to key figures. These media are also available in the Study Area of Mastering Meteorology, and teachers can assign them with automatically graded quizzes.
  - A **Math Review** chapter is added to Mastering Meteorology.
  - New end-of-chapter questions will be included in Mastering Meteorology.

- Significantly **updated and revised content**. A basic function of a college science textbook is to provide clear, understandable presentations that are accurate, engaging, and up-to-date. Our number-one goal is to keep *The Atmosphere* current, relevant, and highly readable for beginning students. In addition to new and improved figures, many discussions and examples have been updated and revised:
  - In Chapter 1, "Earth as a System" is revised with a new "What Powers the Earth System?" subsection. "Ozone Depletion: A Global Issue" is discussed in a new Box.
  - In Chapter 2, "Earth's Rotation and Orbit" is streamlined, and "The Greenhouse Effect" is revised.
  - "Daily Temperature Cycle" and "Annual Temperature Cycle" are presented earlier in Chapter 3, and "Why Temperatures Vary" is reorganized. The chapter's three boxes are updated.
  - In Chapter 4, the "Latent Heat" subsection is expanded, and "Atmospheric Stability" section is improved. A new box discusses the Stuve diagram.

- In Chapter 5, "Precipitation Formation" provides more information on supercooled water, hail formation is expanded, and the radar discussion is updated.
- In Chapter 6, "Measuring Atmospheric Pressure" includes electronic barometers. Pressure changes and friction discussions are revised to make these difficult concepts, and their relationship to wind, easier to understand. The chapter better explains the connections among curved flow aloft, convergence and divergence, rising and sinking motion, and surface wind systems.
- Chapter 7 is significantly reorganized. "Scales of Atmospheric Motion" provides more examples, and "Land and Sea Breeze" is completely revised. "Global Distribution of Pressure and Precipitation" allows better comparison between the two, with discussion of monsoons incorporated into the pressure discussion. The "Jet Streams" section is revised, and the "El Niño, La Niña, and the Southern Oscillation" is expanded to include a direct comparison between normal and El Niño conditions, with a look at the 2015–2016 El Niño.
- In Chapter 8, a new subsection, "Identifying Air Masses on Weather Maps," gives students practical skills, and a new box, "Heat Waves," is added. "Lake Effect Snow" discussion is moved to the "Air-Mass Modification" section.
- The main sections in Chapter 9 are reorganized so that the cyclone models are discussed one after the other. Tables identifying the passage of fronts better match the discussion of frontal elements, and many figures are updated to complement the text.
- Chapter 10 content is substantially improved and streamlined. The "Environment for Thunderstorm Development" subsection is revised, and "Ordinary Cell Thunderstorms" and "Severe Thunderstorms" sections are expanded. The radar discussion is updated under "Tornado Forecasting."

- In Chapter 11, most main sections are renamed and reorganized. Hurricane components are discussed in more detail, and the section "Tracking and Monitoring Hurricanes" is updated and expanded to include aircraft reconnaissance.
- Forecasting information already addressed in earlier chapters is condensed in Chapter 12 to focus on updates to "Modern Weather Forecasting," particularly weather satellites, quantitative forecasting, and thermodynamic diagrams.
- Air pollution statistics in Chapter 13 are updated, and the discussion of atmospheric stability improved.
- Chapter 14 incorporates the most recent IPCC findings. "Predicting Future Climate Change" is revised and updated.
- Chapter 15 is streamlined to focus on controls of climate and the main differences between climate types.
- In Chapter 16, the discussion of mirages is improved.

Distinguishing Features

Focus on Readability and Student Understanding

The language of this text is straightforward and *written to be understood*. Clear, readable discussions with a minimum of technical language are the rule. Frequent headings and subheadings help students follow discussions and identify the important ideas presented in each chapter. In the fourteenth edition, we have continued to improve readability by examining chapter organization and flow and by writing in a more personal style. Every chapter has been condensed to streamline the material and focus on key concepts. Significant portions of several chapters were rewritten and reorganized to improve the flow from one concept to the next.

This course is intended for general-education students taking their first meteorology course. It does not try to go into every detail about weather systems—there are more advanced courses for that. While this book is written at a general-education level, it can certainly be used as a launching point for students who want to pursue the study of meteorology.

Focus on Basic Principles

Although many topical issues are addressed in the fourteenth edition of *The Atmosphere*, it should be emphasized that the main focus of this new edition remains the same: to promote student understanding of basic principles. As much as possible, we have attempted to provide the reader with a sense of the observational techniques and reasoning processes that constitute the science of meteorology.

Additional Learning Aids

In addition to the new and expanded learning path, the fourteenth edition continues to include these important learning aids:

- **Eye on the Atmosphere** features real-world imagery paired with active-learning questions to give students a chance to practice visual analysis tasks as they read. Instructors can discuss these in class or assign the questions to students from the book or MasteringMeteorology.
- Every chapter includes several **You might have wondered . . .** (formerly Students Sometimes Ask) features. Instructors and students continue to react favorably and indicate that the questions and answers sprinkled through each chapter add interest and relevance to discussions.
- The new edition continues to highlight **severe and hazardous weather**. Atmospheric hazards adversely affect millions of people worldwide every day. Severe weather events have a significance and fascination that go beyond ordinary weather phenomena. In addition to the two chapters focused entirely on thunderstorms and tornadoes (Chapter 10) and hurricanes (Chapter 11), the text contains 15 Severe and Hazardous Weather boxes devoted to a broad variety of topics—heat waves, winter storms, floods, air pollution episodes, drought, wildfires, cold waves, and more. Each box now includes **Weather Safety tips** and one or two active-learning questions to help students test their understanding and link these events to critical chapter concepts.

Acknowledgments

Writing a college textbook requires the talents and cooperation of many people. It is truly a team effort, and the authors are fortunate to be part of an extraordinary team at Pearson Education. In addition to being great people to work with, all are committed to producing the best textbooks possible. Special thanks to our Executive Editor, Nancy Whilton, who provided insight and guidance at crucial times. We also appreciate our conscientious Content Producer, Chandrika Madhavan, whose job it was to keep track of all that was going on—and a lot was going on. The fourteenth edition was certainly improved by the talents of our developmental editor, Veronica Jurgena. Many thanks. It was the job of the production team, led by Heidi Allgair at Cenveo® Publisher Services, to turn our manuscript into a finished product. The team also included copyeditor Sally Peyrefitte and photo researcher Kristin Piljay. We think these talented people did great work. All are true professionals, with whom we are very fortunate to be associated.

Working with Dennis Tasa, who is responsible for all of the text's outstanding illustrations, is always special for us. He has been part of our team for more than 30 years. We value not only his artistic talents, hard work, patience, and imagination, but his friendship as well.

Many thanks also go to those colleagues who prepared in-depth reviews. Their critical comments and thoughtful input helped guide our work and clearly strengthened the text. Special thanks to:

Markus Buker, Western Illinois University
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Jian duCaines, University of Louisville
Albert Owino, Western Connecticut State University
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Matthew Van Den Broeke, University of Nebraska

We are very grateful to Neva Duncan-Tabb (St. Petersburg College), who authored the *Instructor Resource Manual*, and to Jennifer Johnson (Ferris State University) for writing the *Test Bank*. We'd also like to thank Michael Burger and Sean Colgan for their help with Integrated Mobile Media.

We would like to welcome Redina Herman to the team. Redina has a PhD in atmospheric science from the University of Illinois, Urbana–Champaign. She has been teaching introductory and advanced meteorology courses for 15 years. Redina is involved in science education research and won the Western Illinois University College of Arts and Sciences award for Outstanding Teaching with Technology. Redina is also Western Illinois University's representative to the University Corporation for Atmospheric Research (UCAR), which runs the National Center for Atmospheric Research (NCAR). She adds a great deal of knowledge, experience, and enthusiasm to the team.

Last, but certainly not least, we gratefully acknowledge the support and encouragement of our significant others, Nancy Lutgens, Joanne Bannon, and Owen Finch. Preparation of *The Atmosphere*, fourteenth edition, would have been far more difficult without their patience and understanding.

Fred Lutgens
Ed Tarbuck

Redina Herman

Digital & Print Resources

For Students & Teachers

Mastering Meteorology™ with Pearson eText. The Mastering platform is the most widely used and effective online homework, tutorial, and assessment system for the sciences. It delivers self-paced tutorials that provide individualized coaching, focus on course objectives, and respond to each student's progress. The Mastering system helps teachers maximize class time with customizable, easy-to-assign, and automatically graded assessments that motivate students to learn outside class and arrive prepared for lecture.

Mastering Meteorology offers the following:

- Assignable activities that include GIS-inspired MapMaster™ interactive maps, Encounter Meteorology Google Earth Explorations, Videos, Geoscience Animations, Map Projection Tutorials, GeoTutor coaching activities on the toughest topics in the geosciences, GEODe Tutorials, end-of-chapter questions and exercises, reading quizzes, Test Bank questions, and more.
- A student Study Area with GIS-inspired MapMaster™ interactive maps, GEODe Tutorials, Videos, Geoscience Animations, web links, glossary flashcards, *In the News* articles, chapter quizzes, an optional Pearson eText, and more.

Pearson eText gives students access to the text whenever and wherever they can access the Internet. Features of Pearson eText include:

- Accessibility via smartphones and tablets (screen-reader ready).
- Seamlessly integrated videos and other rich media.
- Configurable reading settings, including resizable type and night-reading mode.

- Instructor and student note-taking, highlighting, bookmarking, and search.

www.masteringmeteorology.com.

***Hazard City* for Mastering Geography** (0321970349) is a collection of 11 online problem-solving assignments in *Mastering Geography and Meteorology*™ that demonstrate the work of practicing geoscientists and environmental professionals. The activities allow the student to step into the role of a practicing geoscientist to analyze potential disasters in the fictional town of *Hazard City*. Students learn to research and explore on their own in areas such as Map Reading, Ground Water Contamination, Volcanic Hazard Assessment, Earthquake Damage Assessment, Shoreline Property Assessment, and much more.

www.masteringmeteorology.com

- ***Geoscience Animation Library on DVD*, 5th Edition [0321716841]** Created through a unique collaboration among Pearson's leading geoscience authors, this resource offers over 100 animations covering the most difficult-to-visualize topics in meteorology, Earth science, physical geography, physical geology, and oceanography. Animations include audio narration and text transcript, with assignable multiple-choice quizzes to select animations in Mastering Meteorology to help students master these core physical process concepts.
- ***Earth Report* Videos on DVD [0321662989]** This three-DVD set is designed to help students visualize how human decisions and behavior have affected the environment and how individuals are taking steps toward recovery. With topics ranging from poor land management promoting the devastation of river systems in Central America to the struggles for electricity in China and Africa, these 13 videos from Television for the Environment's global *Earth Report*

series recognize the efforts of individuals around the world to unite and protect the planet. Teachers can assign video clips with assessment in Mastering Meteorology.

For Students

- ***Exercises for Weather & Climate*, 9th edition, by Greg Carbone [0134041364]** This bestselling exercise manual's 17 exercises encourage students to review important ideas and concepts through problem solving, simulations, and guided thinking. The graphics program and computer-based simulations and tutorials help students grasp key concepts. Now with mobile-enabled Pre-Lab Videos and Pre- and Post-Lab quizzes in Mastering Meteorology, this manual is designed to complement any introductory meteorology or weather and climate course.
- ***Goode's World Atlas*, 23rd edition [0133864642]** First published by Rand McNally in 1923, Goode's World Atlas is the gold standard for college reference atlases. It features hundreds of physical, political, and thematic maps, graphs, and tables, as well as a comprehensive pronouncing index. The 23rd Edition introduces dozens of new maps, incorporating the latest geographic scholarship and technologies, with expanded coverage of the Canadian Arctic, Europe's microstates, Africa's island states, and U.S. cities. It introduces several new thematic maps on critical topics such as: oceanic environments, earthquakes and tsunamis, desertification vulnerability, maritime political claims, megacities, human trafficking, labor migration . . . and many more topics important to contemporary geography. Available in eText formats from Pearson.
- ***Dire Predictions: Understanding Global Climate Change*, 2nd edition, by Mike Mann and Lee Kump [0133909778]** Periodic reports from the Intergovernmental Panel on Climate Change (IPCC) evaluate the risk of climate change brought on by humans. In just over 200 pages, this practical text presents and expands upon the essential findings of the IPCC in a visually stunning and undeniably powerful way to the lay reader. Scientific findings that provide validity to the implications of climate change are presented in clear-cut graphic elements, striking

images, and understandable analogies. The second edition covers the latest climate change data and scientific consensus from the IPCC *Fifth Assessment Report* and integrates mobile media links to online media. The text is also available in various eText formats, including as a secondary eText upgrade option from *Elemental Geosystems' Mastering Geography*™ courses.

- ***Encounter Physical Geography* by Jess C. Porter and Stephen O'Connell [0321672526]** Pearson's Encounter Series provides rich, interactive explorations of geoscience concepts through Google Earth activities, covering a range of topics in meteorology and physical geography. For those who do not use Mastering Meteorology, all chapter explorations are available in print workbooks, as well as in online quizzes at www.mygeoscienceplace.com, accommodating different classroom needs. Each exploration consists of a worksheet, a corresponding Google Earth KMZ file, and online quizzes whose results can be e-mailed to teachers.

For Teachers

Learning Catalytics is a "bring your own device" student engagement, assessment, and classroom intelligence system. With Learning Catalytics, you can:

- Assess students in real time, using open-ended tasks to probe student understanding.
- Understand immediately where students are and adjust your lecture accordingly.
- Improve your students' critical-thinking skills.
- Access rich analytics to understand student performance.
- Add your own questions to make Learning Catalytics fit your course exactly.
- Manage student interactions with intelligent grouping and timing.

Learning Catalytics is a technology that has grown out of 20 years of cutting-edge research, innovation, and implementation of interactive teaching and peer instruction. Available integrated with Mastering Meteorology.

- ***Instructor Resource Manual* (download only) by Neva Duncan-Tabb, St. Petersburg College [0134800923]** The *Instructor Resource Manual* is intended as a resource for both new and experienced instructors. It includes a variety of lecture outlines, teaching tips, advice about how to integrate visual supplements (including the Mastering Meteorology resources), answers to the textbook chapter questions, and various other ideas for the classroom.
  See www.pearsonhighered.com/irc.
- **TestGen® Computerized *Test Bank* (download only) by Jennifer Johnson, Ferris State University [0134800907]** TestGen® is a computerized test generator that lets instructors view and edit *Test*

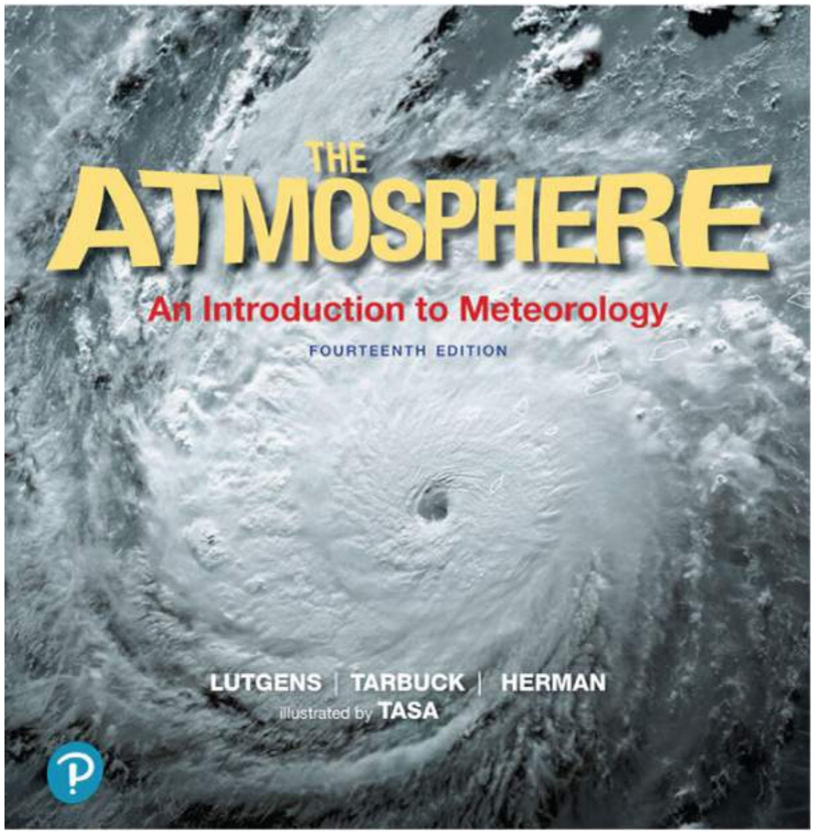
Bank questions, transfer questions to tests, and print tests in a variety of customized formats. This *Test Bank* includes more than 2000 multiple-choice, fill-in-the-blank, and short-answer/essay questions. Questions are correlated to the text's Learning Outcomes, Pearson's Global Science Outcomes, the section of each chapter, the revised U.S. National Geography Standards, and Bloom's taxonomy to help instructors better map the assessments against both broad and specific teaching and learning objectives. The *Test Bank* is also available in Microsoft Word and is importable into systems such as Blackboard.
See www.pearsonhighered.com/irc.

- ***Instructor Resources*** **[0134800915]** Instructor Resources is a collection of resources to help teachers make efficient and effective use of their time. All digital resources can be found in one well-organized, easy-to-access place. The resources include:
  - All textbook images as JPEGs, PDFs, and PowerPoint™ presentations.
  - Pre-authored Lecture Outline PowerPoint™ presentations, which outline the concepts of each chapter with embedded art and can be customized to fit teachers' lecture requirements.
  - "Clicker" questions in PowerPoint™, which correlate to the text's Learning Outcomes, U.S. National Geography Standards, and Bloom's taxonomy.
  - The TestGen software, *Test Bank* questions, and answers for both MACs and PCs.
  - Electronic files of the *Instructor Resource Manual* and *Test Bank*.

This Instructor Resource content is available online via the Instructor Resources section of Mastering Meteorology and www.pearsonhighered.com/irc.

Contents

The Perfect Storm of Rich Media and Active Learning Tools



Streamlined Learning Path Enables students to Comprehend and Apply Key Concepts

Focus on CONCEPTS

Each statement represents the primary learning objective for the corresponding major heading within the chapter. After you complete the chapter, you should be able to:

- Explain what causes the Sun angle and length of daylight to change throughout the year. Describe how these changes result in seasonal changes in temperature (2.1).
- Describe the different forms of energy and heat in the atmosphere: kinetic energy, potential energy, latent heat, and sensible heat (2.2).
- List and describe the three mechanisms of heat transfer (2.3).
- Describe what happens to incoming solar radiation (2.4).
- Explain how the greenhouse effect works and why it is important (2.5).
- Describe the major components of Earth's annual energy budget (2.6).

CONCEPT CHECKS 2.1

- Briefly explain the primary causes of the seasons.
- What is the significance of the Tropic of Cancer and the Tropic of Capricorn?
- After examining Table 2.1, write a general statement that relates the season, latitude, and the length of daylight.

NEW! Active Learning Path An improved learning path now clarifies connections, highlights major concepts and reinforces key ideas as students move through the chapter—leading to greater mastery.

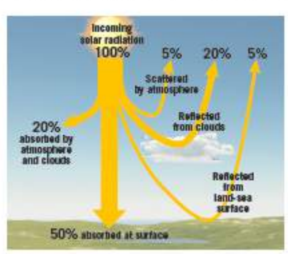
CONCEPTS IN REVIEW

2.4 What Happens to Incoming Solar Radiation?

- Describe what happens to incoming solar radiation.

Key Terms: transmission, absorptivity, reflection, scattering, albedo, diffused light

- Approximately 50 percent of the solar radiation that strikes the atmosphere reaches Earth's surface. About 30 percent is reflected back to space. Clouds and the atmosphere's gases absorb the remaining 20 percent of the incoming solar energy.



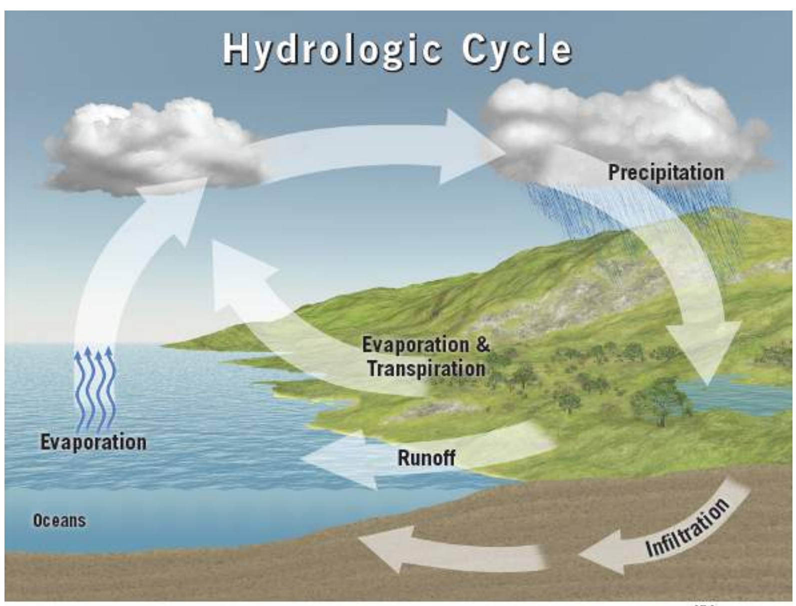
NEW! Key concepts highlighted in every section, serve as guideposts along the learning path helping students synthesize the section information.

front produces roughly the same amount of lifting as a warm front, but over a shorter distance, the precipitation is generally more intense but of shorter duration. A marked temperature drop and wind shift from the southwest to the northwest usually accompanies the passage of a cold front.

Prior to the arrival of a cold front, an area experiences an increase in winds from a southerly direction and warm temperatures, while a line of thunderstorms may be visible in the distance.

The weather following the passage of a cold front is dominated by subsiding air within a continental polar (cP) air mass.

UPDATED! Figures make learning easier by illustrating processes and examples in each chapter. Once again we are privileged to work with Dennis Tasa, whose artistic creations are stunning. There are **129 updated figures** that are new or substantially revised to help clarify difficult concepts. There are **49 updated photographs** of real-world weather situations to keep the textbook current and relevant.



▲ SMARTFIGURE 4.1 Earth's hydrologic cycle

Video
Hydrologic Cycle

NEW! Beyond the Textbook features 1-2 links to websites with atmospheric, weather, or climate data (animated maps, tables, diagrams, etc.) Students are asked questions based on current conditions or a specific locale. This allows students to see how concepts in the chapter play out in real life and in real time.

Beyond the Textbook

1. Water Vapor Satellite Loop

Water vapor provides the primary fuel for the stormy weather we experience. Watch the water vapor loop from GOES EAST at: http://www.ssec.wisc.edu/data/geo/. Click the button next to "Water Vapor

NEW! Weather Safety Tips Weather safety is fully integrated into the textbook. Every Severe & Hazardous Weather feature now contains **Weather Safety tips**. Weather safety tips are also added to the text in several chapters.

WEATHER SAFETY Southern California isn't the only place where wind can create dangerous fire hazards. These conditions can occur in any part of the United States. The National Weather Service issues a *Red Flag Warning* when strong winds, low relative humidity, and dry vegetation combine to create conditions in which fires will ignite quickly and grow rapidly. The following safety advice is given for areas under a Red Flag Warning:

- If you see even a small fire, report it immediately.
- Don't light fires, including campfires and barbeque grills.
- Don't park your car on or drive over dry grass.

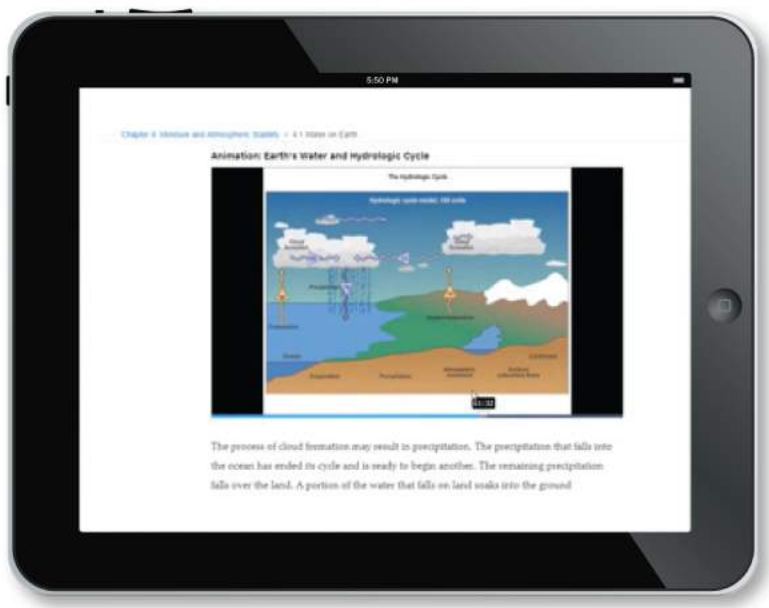
Continuous Learning Before, During and After Class with Mastering Meteorology

Mastering Meteorology: Mastering Meteorology delivers engaging, dynamic learning opportunities focusing on course objectives and responsive to each student's progress–that are proven to help students absorb meteorology course material and understand challenging meteorology processes and concepts.

Mobile Media and Reading Assignments Ensure Students Come to Class Prepared.

NEW! Interactive Pearson eText gives students access to the text, anytime, anywhere. Pearson eText features include:

- Full eReader functionality
- Seamlessly integrated videos and other rich media.
- Accessible (screen-reader ready).
- Configurable reading settings, including resizable type and night reading mode.
- Instructor and student note-taking, highlighting, bookmarking, and search.



Pre-Lecture Reading Quizzes are easy to customize and assign

Reading Questions ensure that students complete the assigned reading before class. Reading Questions are 100% mobile ready and ca eted by students on mobile devices.

Learning Catalytics, a “bring your own device” student engagement, assessment, and classroom intelligence system, allows students to use their smartphone, tablet, or laptop to respond to questions in class.

NEW & UPDATED! Eye on the Atmosphere which feature real-world imagery paired with active-learning questions, giving students a chance to practice visual analysis tasks as they read.

eye on the ATMOSPHERE 3.1

Imagine being at this beach on a warm, sunny summer afternoon.

Apply What You Know

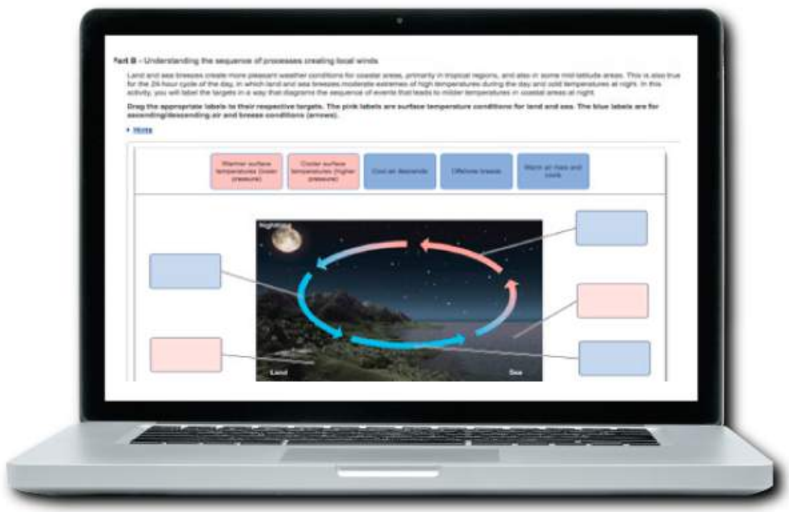
1. Describe the temperatures you would expect if you measured the beach surface and then at a depth of 12 inches.
2. If you stood waist deep in the water and measured the water's surface temperature and the temperature at a depth of 12 inches, how would these measurements compare to those taken on the beach?

Continuous Learning with Mastering Meteorology

Easy to Assign, Customize, Media-Rich, and Atomically Graded Assignments.

NEW! MapMaster2.0 activities are inspired by GIS and allow students to layer various thematic maps to analyze spatial patterns and data at regional and global scales. Now, **fully mobile**, activities include enhanced analysis tools, such as split screen, the ability for students to geolocate themselves in the data, and the ability for students to upload their own data. This tool includes zoom and annotation functionality, with hundreds of map layers leveraging recent data from sources such as NOAA, NASA, USGS, United Nations, CIA, World Bank, UN, PRB, and more.

HALLMARK! GeoTutors. Highly visual coaching items with hints and specific wrong answer feedback help students master the toughest topics.



HALLMARK! Encounter Activities (GoogleEarth) activities provide rich, interactive explorations of human geography concepts, allowing students to visualize spatial data and tour distant place on the virtual globe.

HALLMARK! SmartFigures are brief, narrated video lessons that examine and explain concepts illustrated by key figures within the text. Students access SmartFigures on their mobile devices by scanning Quick Response (QR) codes next to key figures. These media are also available in the Study Area and can be assigned through Mastering Meteorology.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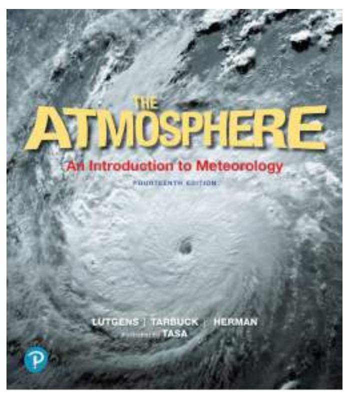
Resources for YOU, the Instructor

Mastering Meteorology provides you with everything you need to prep for your course and deliver a dynamic lecture, in one convenient place. Resources include:

MEDIA ASSETS FOR EACH CHAPTER

- *GeoVideos*
- MapMaster2.0
- Google Earth
- GeoTutors
- PowerPoints



Test Bank

- Test Bank in Microsoft, Word, PDF, and RTF formats
- Computerized Test Bank, which includes all the questions from the printed test bank in a format that allows you to easily and intuitively build exams and quizzes.

Teaching Resources

- Instructor Resource and Support Manual in Microsoft Word and PDF formats
- Teaching with Student Learning Outcomes
- Learning Catalytics: Getting Started
- Lecture and Image PowerPoints
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- Study Area
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Measuring Student Learning Outcomes?

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Chapter 1 Introduction to the Atmosphere

This satellite image shows Hurricane Sandy, called Superstorm Sandy in the media, battering the U.S. east coast on October 30, 2012. This view of the storm is looking south from Canada. Florida is near the top of the image.

Focus on Concepts

Each statement represents the primary learning objective for the corresponding major heading within the chapter. After you complete the chapter, you should be able to:

1. Distinguish between weather and climate, name the basic elements of weather and climate, and list several important atmospheric hazards (1.1).
2. Discuss the nature of scientific inquiry, including the construction of hypotheses and the development of theories (1.2).
3. List and describe Earth's four major spheres. Define *system*, and explain why Earth is considered a system (1.3).
4. List the major gases composing Earth's atmosphere and identify the components that are most important meteorologically (1.4).
5. Interpret a graph that shows changes in air pressure from Earth's surface to the top of the atmosphere. Sketch and label a graph that shows the thermal structure of the atmosphere (1.5).

Earth's atmosphere is unique. No other planet in our solar system has an atmosphere with the exact mixture of gases or the heat and moisture conditions necessary to sustain life as we know it. The gases that make up Earth's atmosphere and the controls to which they are subject are vital to our existence. In this chapter we begin our examination of the ocean of air in which we all must live.

1.1 Focus on the Atmosphere

LO 1 Distinguish between weather and climate, name the basic elements of weather and climate, and list several important atmospheric hazards.

Weather influences our everyday activities, our jobs, and our health and comfort. Many of us pay attention to the weather only when it inconveniences us or when it adds to our enjoyment of outdoor activities. Nevertheless, few other aspects of our physical environment affect our lives more than the phenomena we collectively call the weather.

Weather in the United States

The United States occupies an area that stretches from the tropics to the Arctic Circle. It has thousands of miles of coastline and extensive regions far from the influence of the ocean. Some landscapes are mountainous, and others are dominated by plains. Pacific storms strike the west coast, while the eastern states are sometimes influenced by events in the Atlantic and the Gulf of Mexico. The states in the center of the country commonly experience weather events triggered when frigid southward-bound Canadian air masses clash with northward-moving tropical air masses from the Gulf of Mexico.

The United States likely has the greatest variety of weather of any country in the world. Severe weather events such as tornadoes, flash floods, and intense thunderstorms, as well as hurricanes and blizzards, are collectively more frequent and more damaging in the United States than in any other nation (Figure 1.1). Beyond its direct impact on the lives of individuals, weather strongly affects the U.S. economy through its influence on agriculture, energy use, water resources, and transportation.

Figure 1.1 An extraordinary winter

The winter of 2013–2014 brought record-breaking cold and snow to much of the eastern half of the conterminous United States. Meanwhile, Alaska and much of the West were much warmer and drier than usual.

Weather influences our lives a great deal. Yet it is also important to realize that people influence the atmosphere and its behavior as well. There are, and will continue to be, significant economic, political, and scientific decisions to make involving these human impacts. Dealing with the effects of and controlling air pollution is one example (Figure 1.2). Another is the ongoing effort to assess and address global climate change. There is clearly a need for increased awareness and understanding of our atmosphere and its behavior.

Figure 1.2 People influence the atmosphere

China is plagued by air quality issues. Major contributors of air pollutants in the region are coal-fired electricity generating plants.

Meteorology, Weather, and Climate

The subtitle of this book includes the word *meteorology*. **Meteorology** is the scientific study of the atmosphere and the phenomena that we usually refer to as *weather*. Acted on by the combined effects of Earth's motions and energy from the Sun, our planet's formless and invisible envelope of air reacts by producing an infinite variety of weather, which in turn creates the basic pattern of global climates. Although not identical, weather and climate have much in common.

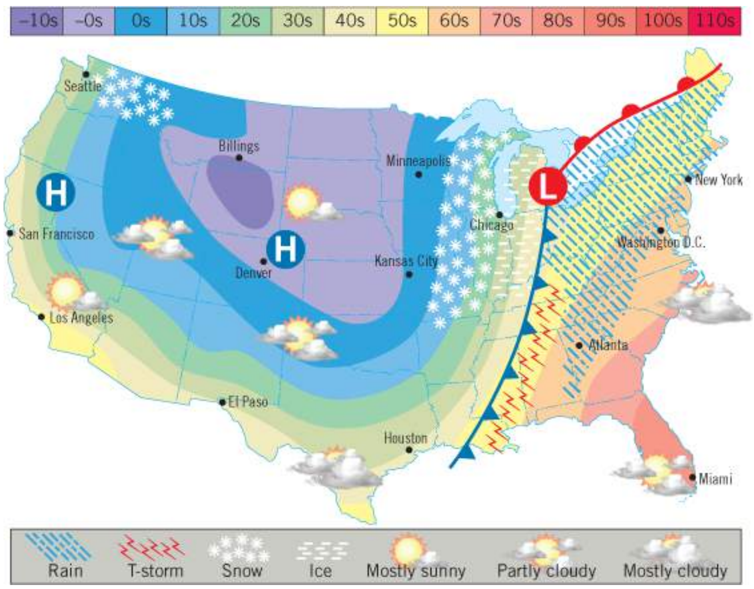
Weather refers to the state of the atmosphere at a given time and place. Weather is constantly changing, sometimes from hour to hour and at other times from day to day. Whereas changes in the weather are continuous and sometimes seemingly erratic, it is nevertheless possible to arrive at a generalization of these variations. Such a description of aggregate weather conditions is termed **climate**. It is based on observations that have been accumulated over many decades. *Climate* is often defined simply as "average weather," but this definition is inadequate. An accurate portrayal of an area's climate must also include variations and extremes, as well as the probabilities that such departures from the norm will take place. For example, farmers need to know the average temperature during their area's growing season, but they must also know the date in the spring when the last freezing temperatures are most likely to occur.

> Weather refers to the state of the atmosphere at a given time and place.

Maps like the one in Figure 1.3 are familiar to everyone who checks the weather report from a website, a newspaper, or on television. In addition to showing predicted high temperatures for the day, this type of map shows other basic weather information about cloud cover, precipitation, and the location of fronts.

Figure 1.3 Typical weather map for a day in late December

The colored bands show predicted high temperatures for the day.

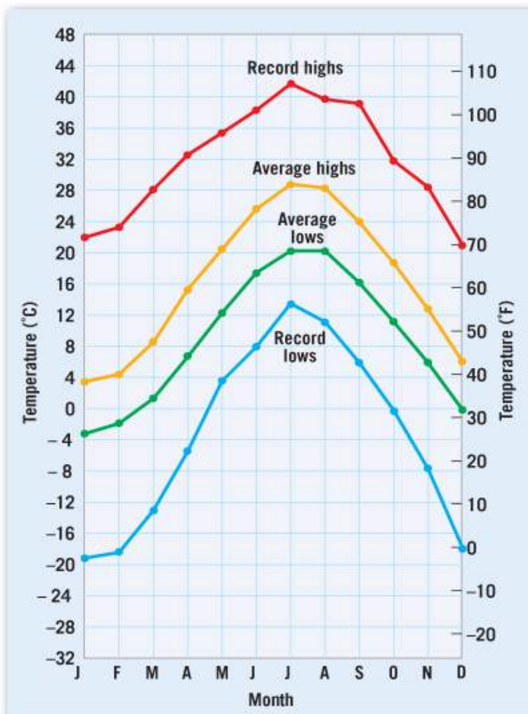


Suppose you were planning a vacation trip to an unfamiliar place. You would probably want to know what kind of weather to expect. Such information would help you select which clothes to pack and could influence what you decide to do during your stay. Unfortunately, weather forecasts that go beyond a few days are not very dependable. Thus, it may not be possible to get a reliable weather report about the conditions you are likely to encounter during your vacation.

Instead, you might ask someone who is familiar with the area about what kind of weather to expect. “Are thunderstorms common?” “Does it get cold at night?” “Are the afternoons sunny?” What you are seeking is information about the climate, the conditions that are typical for that place. Another useful source of such information is the great variety of climate tables, maps, and graphs that are available. For example, the graph in Figure 1.4 shows average daily high and low temperatures for each month, as well as extremes, for New York City.

Figure 1.4 New York City temperatures

In addition to the average maximum and minimum temperatures for each month, extremes are also shown. The graph is based on data collected during a 30-year span and shows that significant departures from the average can occur.



> Climate is the average of all weather data, including extremes, that helps to describe the environment of a place or region.

You might have wondered . . .

Does meteorology have anything to do with meteors?

There is a connection. The term *meteorology* was coined in 340 BCE, when the Greek philosopher Aristotle wrote a book titled *Meteorologica*, which described atmospheric and astronomical phenomena. In Aristotle's day, *anything* that fell from or was seen in the sky was called a meteor. Today, however, we distinguish particles of ice or water in the atmosphere from extraterrestrial objects—meteoroids, or meteors.

Such information could, no doubt, help as you planned your trip. But it is important to realize that *climate data cannot predict the weather*. Although the place may usually (climatically) be warm, sunny, and dry during the time of your planned vacation, you may in fact experience cool, overcast, and rainy weather. A well-known saying summarizes the distinction between weather and climate: "Climate is what you expect, but weather is what you get."

The nature of both weather and climate is expressed in terms of the same basic properties, or *elements*, that are measured regularly. The most important are (1) the *temperature* of the air, (2) the *humidity* of the air, (3) the type and amount of *cloudiness*, (4) the type and amount of *precipitation*, (5) the *pressure* exerted by the air, and (6) the speed and direction of the *wind*. These elements constitute the variables by which weather patterns and climate types are depicted, and many of these are shown as map symbols in Figure 1.3. Although you will study these elements separately at first, keep in mind that they are very much interrelated. A change in one of the elements often produces changes in the others.

Atmospheric Hazards

Natural hazards are a part of living on Earth. Every day they adversely affect millions of people worldwide and are responsible for staggering damages. Some, such as earthquakes and volcanic eruptions, are geologic in nature. Many others are related to the atmosphere.

For most people, severe weather events are far more fascinating than ordinary weather phenomena. A spectacular lightning display generated by a severe thunderstorm can elicit both awe and fear. Of course, hurricanes and tornadoes attract a great deal of much-deserved attention. A single tornado outbreak or hurricane can cause billions of dollars in property damage, much human suffering, and many deaths. The chapter-opening satellite image of Hurricane Sandy and the tornado damage depicted in Figure 1.5 are good examples of such severe weather. Severe storms are covered extensively in Chapters 10 and 11.

Figure 1.5 Impacts of severe weather

Tornado damage to a grain elevator in Eureka, Kansas, July 8, 2016.

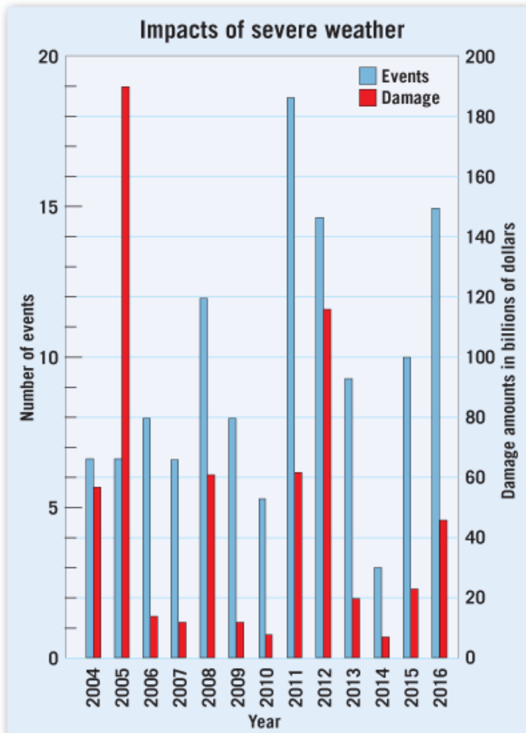
Other atmospheric hazards also adversely affect us. Some are storm related, such as blizzards, hail, and freezing rain. Others are not direct results of storms. Heat waves, cold waves, fog, wildfires, and drought are important examples. In some years, the loss of human life due to excessive heat or bitter cold exceeds that caused by all other weather events combined. Although severe storms and floods usually generate more attention, droughts can be just as devastating and carry an even bigger price tag, while extreme heat is the number-one killer worldwide.

Between 2004 and 2016, the United States experienced 102 weather-related disasters in which overall damages and costs reached or exceeded $1 billion (Figure 1.6). In addition to taking more than 4100 lives, these events exacted economic costs that exceeded $600 billion! Every day our planet experiences an incredible assault by the atmosphere, so it is important to develop an awareness and understanding of these significant weather events.

Figure 1.6 **Billion-dollar weather events**

Between 2004 and 2016, the United States experienced 102 weather-related disasters in which overall damages and costs reached or exceeded $1 billion. The blue bar graph shows the number of events that occurred each year, and the red bar graph shows damage amounts in billions of dollars (adjusted to 2016 dollars). The total losses for these events exceeded $600 billion!

(Data from NOAA)



Concept Checks 1.1

- Define *meteorology*. Define and distinguish weather and climate.
- List the basic elements of weather and climate.
- List five storm-related atmospheric hazards and three atmospheric hazards that are not directly storm related.

1.2 The Nature of Scientific Inquiry

LO 2 Discuss the nature of scientific inquiry, including the construction of hypotheses and the development of theories.

Developing an understanding of how science is done and how scientists work is an important theme in this book. As members of a modern society, we are constantly reminded of the benefits derived from science. But what exactly is the nature of scientific inquiry? Science is a process of producing knowledge. The process depends both on making careful observations and on creating explanations that make sense of the observations. The types of data that are collected often help to answer a well-defined question about the natural world, such as "Why does fog more often develop on cool clear nights, rather than warm overcast nights?" or "What causes rain to form in one cloud type, but not in another?"

All science is based on the assumption that the natural world behaves in a consistent and predictable manner that is comprehensible through careful, systematic study. The overall goal of science is to discover the underlying patterns in nature and then to use the knowledge gained to make predictions about what should or should not be expected, given certain facts or circumstances. For example, by understanding the forces that influence the movement of air, meteorologists can predict the approximate time and place of the passage of a cold front, which causes temperatures to drop.

Hypothesis

A scientific **hypothesis** is a proposed explanation for a certain phenomenon that occurs in the natural world. For such an explanation to be considered a hypothesis, it must be *testable*. Therefore, before a hypothesis can become an accepted part of scientific knowledge, it must pass objective testing and analysis. This process requires that *predictions* can be made based on the hypothesis being considered. Put another way, hypotheses must fit observations other than those used to formulate them in the first place. Hypotheses that fail rigorous testing are discarded. The history of science is littered with discarded hypotheses. One of the best known is the Earth-centered model of the universe—a proposal that was supported by the apparent daily motion of the Sun, Moon, and stars around Earth. More detailed astronomical observations disproved this hypothesis.

> A hypothesis is a proposed explanation for a certain phenomenon that occurs in the natural world.

Theory

When a hypothesis has survived extensive scrutiny and when competing hypotheses have been eliminated, it may be elevated to the status of a scientific **theory**. In everyday language, we may say that something is "only a theory." But among the scientific community, a theory is a well-tested and widely accepted view that best explains certain observable facts.

Some theories that are extensively documented and extremely well supported by data are comprehensive in scope. An example from the Earth sciences is the theory of plate tectonics, which provides the framework for understanding the origins of mountains, earthquakes, and volcanic activity. It also explains the evolution of continents and ocean basins through time. As you will see in Chapter 14, this theory also helps us understand some important aspects of climate change through long spans of geologic time.

> A scientific theory is a well-tested and widely accepted view that the scientific community agrees best explains certain observable facts.

Scientific Inquiry

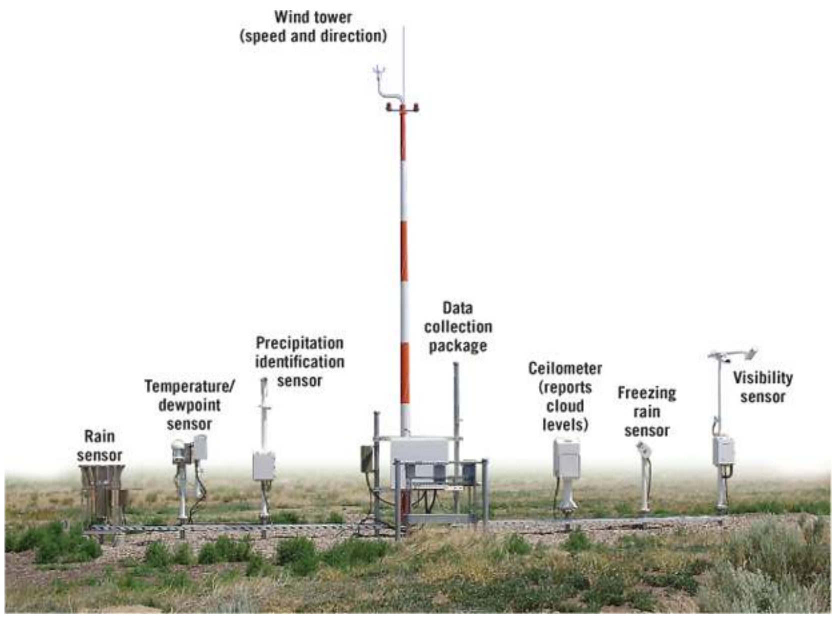
The processes just described, in which scientists gather data through observations and formulate scientific hypotheses and theories, is called the *scientific method*. Contrary to popular belief, the scientific method is not a standard recipe that scientists apply in a routine manner to unravel the secrets of our natural world. Rather, it is an endeavor that involves creativity and insight. Rutherford and Ahlgren put it this way: “Inventing hypotheses or theories to imagine how the world works and then figuring out how they can be put to the test of reality is as creative as writing poetry, composing music, or designing skyscrapers.”*

Scientists have no fixed path that leads unerringly to scientific knowledge. Nevertheless, most scientific investigations involve the following:

- A question is raised about the natural world.
- Scientific data that relate to the question are collected (Figure 1.7).
- Questions that relate to the data are posed, and one or more working hypotheses that may answer these questions are proposed.
- Observations, experiments, and models are developed to test the hypotheses.
- The hypotheses are accepted, modified, or rejected, based on extensive testing.
- Data and results are shared with the scientific community for critical examination and further testing.

Figure 1.7 Observation and measurement are basic parts of scientific inquiry

Automated observing systems, like the one shown, are designed to measure cloud coverage; take temperature and dew-point measurements; determine wind speed and direction; and even record present weather—such as whether it is raining or snowing.



Some scientific discoveries result from purely theoretical ideas that stand up to extensive examination. Some researchers use high-speed computers to simulate what is happening in the "real" world. These models are useful for dealing with natural processes that occur on very long time scales or that take place in extreme or inaccessible locations. Still other scientific advancements have been made when something totally unexpected happened during an experiment. These serendipitous discoveries are more than pure luck; as the nineteenth-century French scientist Louis Pasteur said, "In the field of observation, chance favors only the prepared mind."**

Scientific knowledge is acquired through several avenues, so it might be best to describe the nature of scientific inquiry as the *methods* of science rather than *the* scientific method. In addition, it should always be remembered that even the most compelling scientific theories are still simplified explanations of the natural world.

You might have wondered . . .

How do a hypothesis and a theory differ from a scientific law?

A *scientific law* is a basic principle that describes a particular behavior of nature that is generally narrow in scope and can be stated briefly—often as a simple mathematical equation. Because scientific laws have been shown time and time again to be consistent with observations and measurements, they are rarely discarded but may require modifications to fit new findings. For example, Newton's laws of motion are still useful for everyday applications (NASA uses them to calculate satellite trajectories), but they do not work at velocities approaching the speed of light. Einstein's theory of relativity is instead applied in these circumstances.

Concept Checks 1.2

- How is a scientific hypothesis different from a scientific theory?
- Summarize the basic steps followed in many scientific investigations.

* F. James Rutherford and Andrew Ahlgren, *Science for All Americans* (New York: Oxford University Press, 1990), p. 7.

** Louis Pasteur, quoted in *Science, History and Social Activism*, edited by Everett Mendelsohn, Garland E. Allen, and Roy M. MacLeod (Dordrecht: Springer, 2001), p. 134.

1.3 Earth as a System

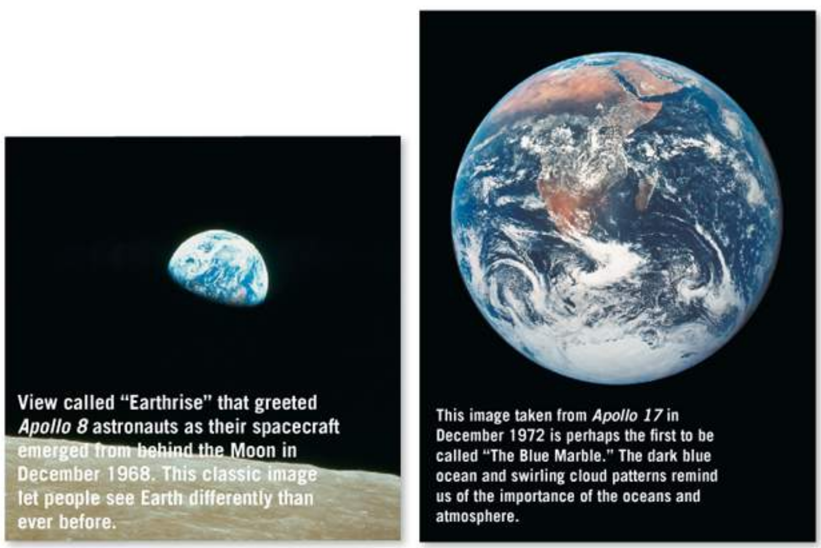
LO 3 List and describe Earth's four major spheres. Define *system*, and explain why Earth is considered a system.

Anyone who studies Earth soon learns that our planet is a dynamic body with many separate but highly interactive parts, or *spheres.* The atmosphere, hydrosphere, biosphere, and lithosphere, along with all of their components, can be studied separately. However, the parts are *not* isolated. Each is related in many ways to the others, producing a complex and continuously interacting whole that we call the *Earth system.*

Earth's Spheres

The images in Figure 1.8 are classics because, for the first time, they let humanity see Earth differently from ever before. These photos profoundly altered our conceptualizations of Earth and remain powerful images decades after they were first viewed. Seen from space, Earth is breathtaking in its beauty and startling in its solitude. The images remind us that our home is, after all, a planet—small, self-contained, and in some ways even fragile. Bill Anders, the *Apollo 8* astronaut who took the "Earthrise" photo, expressed it this way: "We came all this way to explore the Moon, and the most important thing is that we discovered the Earth."

Figure 1.8 Two classic views of Earth from space



View called "Earthrise" that greeted *Apollo 8* astronauts as their spacecraft emerged from behind the Moon in December 1968. This classic image let people see Earth differently than ever before.

This image taken from *Apollo 17* in December 1972 is perhaps the first to be called "The Blue Marble." The dark blue ocean and swirling cloud patterns remind us of the importance of the oceans and atmosphere.

The closer view of Earth from space shown in Figure 1.8 helps us appreciate why the physical environment is traditionally divided into three major parts: Earth's gaseous envelope, the *atmosphere*; the water portion of our planet, the *hydrosphere*; and Earth's solid outer layer, the *lithosphere*. It should be emphasized that our environment is highly integrated and is not dominated by air, water, or rock alone. Instead, the *biosphere*, the life-forms on our planet, extends into each of the three physical realms and is an equally integral part of the planet.

Moreover, the interactions among Earth's four spheres are incalculable. Figure 1.9 provides one easy-to-visualize example. The shoreline is an obvious meeting place for rock, water, and air, and these spheres in turn support life-forms in and near the water. In this scene, ocean waves created by the drag of air moving across the water are breaking against the rocky shore. The force of water, in turn, erodes the shoreline.

Figure 1.9 Interactions among Earth's spheres

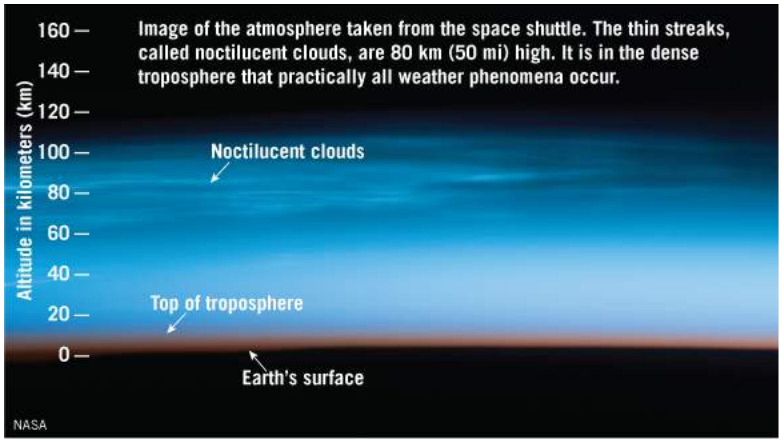
The shoreline is one obvious example of an *interface*—a common boundary where different parts of a system interact. In this scene, ocean waves (*hydrosphere*) that were created by the force of moving air (*atmosphere*) break against a rocky shore (*lithosphere*).

The Earth can be divided into four spheres: the *atmosphere* (air), the *hydrosphere* (water), the *lithosphere* (rock), and the *biosphere* (life-forms).

The Atmosphere

Earth is surrounded by a life-giving gaseous envelope called the **atmosphere** (Figure 1.10). When we watch a high-flying jet plane cross the sky, it seems that the atmosphere extends upward for a great distance. However, when compared to the thickness (radius) of the solid Earth, the atmosphere is a very shallow layer. This thin blanket of air is nevertheless an integral part of the planet. It not only provides the air we breathe, but also acts to protect us from the dangerous radiation emitted by the Sun.

Figure 1.10 **The atmosphere, an integral part of the planet**

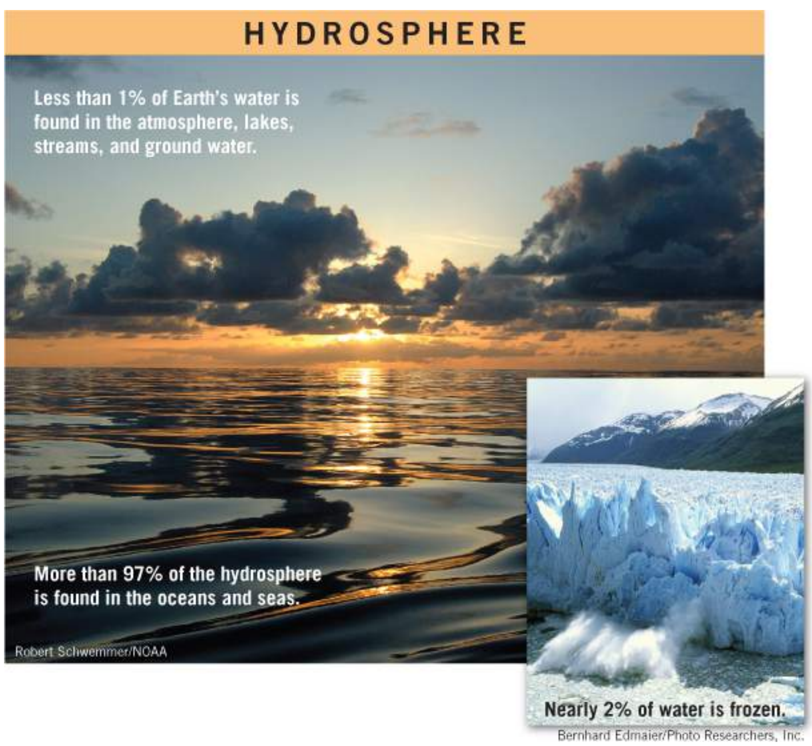


Furthermore, the energy exchanges that continually occur between the atmosphere and Earth's surface and between the atmosphere and space produce the effects we call *weather*. If, like the Moon, Earth had no atmosphere, our planet would not only be lifeless, but many of the processes and interactions that make the surface such a dynamic place could not operate.

The Hydrosphere

More than anything else, water makes Earth unique. The **hydrosphere** is a dynamic mass that is continually on the move, evaporating from the oceans to the atmosphere, precipitating to the land, and running back to the ocean again. The global ocean is certainly the most prominent feature of the hydrosphere, blanketing nearly 71 percent of Earth's surface (Figure 1.11). The hydrosphere also includes the freshwater found in clouds, streams, lakes, and glaciers, as well as that found underground. Although these latter sources constitute only a tiny fraction of the total, they are much more important than their meager percentage indicates. Clouds, of course, play a vital role in many weather and climate processes. In addition, clouds provide the rainfall so essential to life on land.

Figure 1.11 Distribution of water in the hydrosphere



The Lithosphere

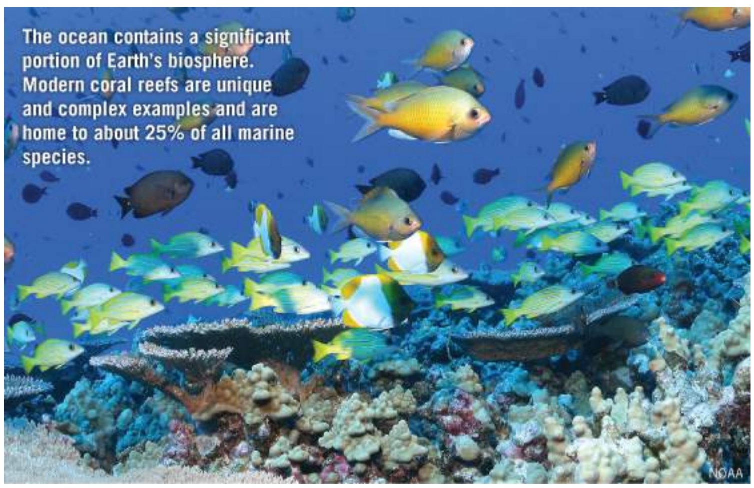
Beneath the atmosphere and the ocean is Earth's rocky outer layer, called the **lithosphere**. The surface of the lithosphere is very uneven and contains high mountainous topography, as well as low areas such as Death Valley—portions of which lie below sea level. Sometimes the lithosphere is referred to as the *geosphere*, in which case scientists include Earth's mantle and core in its description.

Soil, the thin veneer of material at Earth's surface that supports the growth of plants, may be thought of as part of all four spheres. The solid portion is a mixture of weathered rock debris (lithosphere) and organic matter from decayed plant and animal life (biosphere). The decomposed and disintegrated rock debris is the product of weathering processes that require air (atmosphere) and water (hydrosphere). Air and water also occupy the open spaces between the solid particles.

The Biosphere

The **biosphere** includes all life on Earth, including the vast oceans (Figure 1.12). Plants and animals depend on the physical environment for the basics of life. However, organisms do more than just respond to their physical environment. Through countless interactions, life-forms help maintain and alter their physical environment. Without life, the makeup and nature of the atmosphere, hydrosphere, and lithosphere would be very different.

Figure 1.12 **The biosphere includes all life-forms**



The Earth System

Scientists have recognized that to more fully understand our planet, they must learn how its individual components (air, water, land, and life-forms) are interconnected. This endeavor aims to study Earth as a *system*. A **system** is a collection of numerous interacting parts, or *subsystems*, that form a complex whole. Using an interdisciplinary approach, scientists attempt to understand and address many of our global environmental problems.

Most of us hear and use the term *system* frequently. We may service our car's cooling *system*, make use of the city's transportation *system*, and participate in the political *system*. A news report might inform us of an approaching weather *system*. Further, we know that Earth is just a small part of a larger system known as the *solar system*.

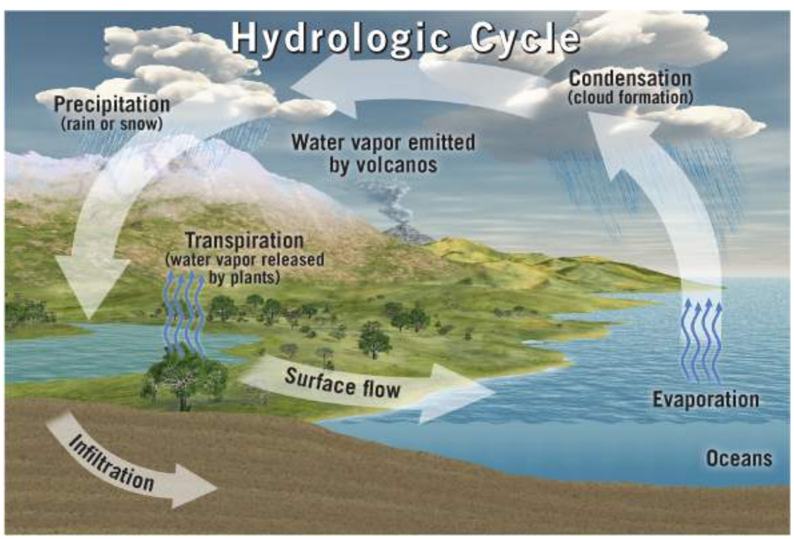
> A system is a collection of interacting, or interdependent, parts that form a complex whole.

Earth as a System

The Earth system has a nearly endless array of subsystems in which matter is recycled over and over again. One familiar loop, or subsystem, is the *hydrologic cycle*. It represents the unending circulation of Earth's water among the hydrosphere, atmosphere, biosphere, and lithosphere (Figure 1.13). Water enters the atmosphere through evaporation from Earth's surface and transpiration from plants. Water vapor (water in the gaseous state) condenses in the atmosphere to form clouds, which in turn produce precipitation that falls back to Earth's surface. Some of the rain that falls onto the land infiltrates (soaks into the ground) and is later taken up by plants or is stored as groundwater, while some flows across the surface toward the ocean.

Figure 1.13 The hydrologic cycle

Water readily changes state from liquid, to gas (vapor), to solid at the temperatures and pressures occurring on Earth. This cycle traces the movements of water among Earth's four spheres. It is one of many subsystems that collectively make up the Earth system.



The parts of the Earth system are linked so that a change in one part can produce changes in any or all of the other parts. For example, during most winter seasons, moisture evaporates from the Pacific Ocean and subsequently falls as rain in the hills of southern California. Sometimes the rainfall is heavy enough to trigger destructive debris flows (Figure 1.14). The processes that move water from the hydrosphere to the atmosphere and then to the lithosphere have a profound impact on the physical environment and on the plants and animals (including humans) that inhabit the affected regions.

Figure 1.14 Heavy rains trigger debris flow

Vehicles trapped by a mudslide on California Highway 58 near Mojave, California, October 16, 2015, following torrential rains. This image provides an example of interactions among different parts of the Earth system.

Humans are *part of* the Earth system, a system in which the living and nonliving components are profoundly interconnected. Therefore, our actions in one sphere can produce changes in all the other spheres. When we burn gasoline and coal, dispose of wastes, and clear the land, we cause other parts of the system to respond, often in unforeseen ways. Throughout this book, you will learn about some of Earth's subsystems, including the hydrologic system and the climate system. Remember that these components *and we humans* are all part of the complex interacting whole we call the Earth system.

What Powers the Earth System?

The Earth system is powered by energy from two sources. The Sun drives external processes that occur in the atmosphere, in the hydrosphere, and at Earth's surface. Weather and climate, ocean circulation, and erosional processes are driven by energy from the Sun. Earth's interior is the second source of energy. Heat remaining from the planet's formation, as well as heat that is continuously generated by radioactive decay, powers the internal processes that produce volcanoes, earthquakes, and mountains.

Concept Checks 1.3

- List and briefly define the four spheres that constitute the Earth system.
- What is a system? List three examples.
- What are the two sources of energy for the Earth system?

1.4 Composition of the Atmosphere

LO 4 List the major gases composing Earth's atmosphere and identify the components that are most important meteorologically.

Sometimes the term **air** is used as if it were a specific gas, but it is not. Rather, air is a *mixture* of many discrete gases, each with its own physical properties, in which varying quantities of tiny solid and liquid particles are suspended. The composition of air is not constant; it varies from time to time and from place to place (Box 1.1). If the water vapor, dust, and other variable components were removed from the atmosphere, we would find that its makeup is very stable up to an altitude of about 80 kilometers (50 miles).

> Air is a *mixture* of many gases, each with its own physical properties, in which tiny solid and liquid particles are suspended.

Box 1.1

Origin and Evolution of Earth's Atmosphere

The air we breathe is a stable mixture of mainly nitrogen and oxygen along with small amounts of other gases, including argon, carbon dioxide, and water vapor. However, our planet's original atmosphere 4.6 billion years ago was substantially different.

Earth’s Primitive Atmosphere

Early in Earth’s formation, the planet’s atmosphere likely consisted of gases most common in the early solar system: hydrogen, helium, methane, ammonia, carbon dioxide, and water vapor. The lightest of these gases, hydrogen and helium, escaped into space because Earth’s gravity was too weak to hold them. Most of the remaining gases were probably largely scattered into space by strong *solar winds* (vast streams of particles) from the young active Sun.

Earth’s first enduring atmosphere was generated by a process called *outgassing*, through which gases trapped in the planet’s interior are released. Outgassing from hundreds of active volcanoes remains an important planetary function worldwide (Figure 1.A). However, early in Earth’s history, when the planet’s interior experienced massive heating and fluid like motion, the gas output must have been immense. Our understanding of modern volcanic eruptions indicates that Earth’s early atmosphere probably consisted of mostly water vapor, carbon dioxide, and sulfur dioxide, with minor amounts of other gases and minimal nitrogen.

Figure 1.A Outgassing

Earth's first enduring atmosphere was formed by a process called *outgassing*, which continues today, from hundreds of active volcanoes worldwide.

Watch Video: The Influence of Volcanic Ash

Equally important, molecular oxygen (O_2) was not present in Earth's atmosphere in appreciable amounts for at least the first 2 billion years of Earth history. Molecular oxygen is often called "free oxygen" because it consists of oxygen atoms that are not bound to other elements, such as hydrogen (in water molecules, H_2O) or carbon (in carbon dioxide, CO_2).

Oxygen in the Atmosphere

As Earth's surface cooled, water vapor condensed to form clouds, and torrential rains began to fill low-lying areas that eventually became the oceans. In those oceans, nearly 3.5 billion years ago, primitive bacteria known as *cyanobacteria* (once called blue-green algae) developed the ability to carry out photosynthesis and began to release oxygen into the water. *Photosynthesis* is the production of energy-rich molecules of sugar from molecules of carbon dioxide (CO_2) and water (H_2O), using sunlight as the energy source. The sugars (glucose and other sugars) generated by photosynthesis are used in metabolic processes by living things, and the by-product of photosynthesis is molecular oxygen.

Initially, the newly released oxygen was readily consumed by chemical reactions with other atoms and molecules (particularly iron) in the ocean. Once the available iron satisfied its need for oxygen and as the number of oxygen-generating organisms increased, oxygen molecules began to build up in the atmosphere. Chemical analyses of rocks suggest that a significant amount of oxygen appeared in the atmosphere as early as 2.3 billion years ago. During the following billion years, oxygen levels in the atmosphere probably fluctuated but remained below current levels. Then, roughly 550 million years ago, the level of free oxygen in the atmosphere began to increase once again. The availability of abundant oxygen in the atmosphere contributed to the proliferation of aerobic life-forms (oxygen-consuming organisms).

Another significant benefit of this "oxygen explosion" is that oxygen molecules (O_2) readily absorb ultraviolet radiation and rearrange themselves to form *ozone* (O_3). Today, ozone is concentrated above the surface in a layer called the *stratosphere*, where it absorbs much of the Sun's ultraviolet radiation that strikes the upper atmosphere. For the first time, Earth's surface was protected from this type of solar radiation, which is particularly harmful to DNA. Marine organisms had always been shielded from ultraviolet radiation by the oceans, but the development of the atmosphere's protective ozone layer made the continents more hospitable.

Apply What You Know

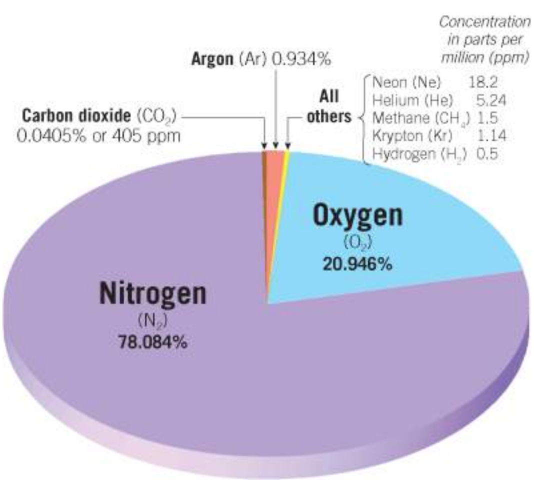
1. What was the source of the gases that composed Earth's first enduring atmosphere?
2. What was the source of the atmosphere's first free oxygen?

Nonvariable Components

As you can see in Figure 1.15, two gases—nitrogen and oxygen—make up about 99 percent of the volume of clean, dry air. Although these gases are the most plentiful components of the atmosphere and are of great significance to life on Earth, they are of little or no importance in affecting weather phenomena. The remaining 1 percent of dry air is mostly the inert gas argon (0.93 percent) plus tiny quantities of other gases listed in Figure 1.15.

Figure 1.15 Composition of the atmosphere

Proportional volume of gases composing dry air. Nitrogen and oxygen obviously dominate.



> Two gases—nitrogen and oxygen—make up about 99 percent of the volume of clean, dry air.

Variable Components

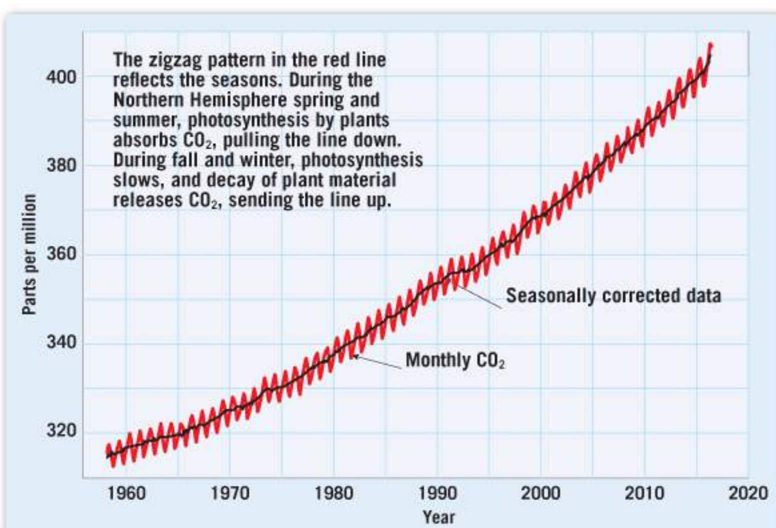
Many of the gases and particles that make up air vary significantly from time to time and place to place. Important examples include carbon dioxide, water vapor, aerosols, and ozone. Although usually present in small percentages, they can significantly affect weather and climate.

Carbon Dioxide

Carbon dioxide, a gas present in only minute amounts (0.0400 percent, or 400 parts per million [ppm]), is nevertheless an important constituent of air. Carbon dioxide is of great interest to meteorologists because it is an efficient absorber of energy and thus influences the heating of the atmosphere. Although the proportion of carbon dioxide in the atmosphere is relatively uniform from place to place and at different heights in the atmosphere, its percentage has been rising steadily for more than a century. Figure 1.16 is a graph that shows the growth in atmospheric CO_2 since 1958. Much of this rise is attributed to the burning of ever-increasing quantities of fossil fuels, such as coal and oil. Some of this additional carbon dioxide is absorbed by the ocean or is used by plants, but more than 40 percent remains in the air. Estimates project that by sometime in the second half of the twenty-first century, atmospheric carbon dioxide will be twice as high as pre-industrial levels.

Smartfigure 1.16 Monthly CO_2 concentrations

Atmospheric CO_2 has been measured at Mauna Loa Observatory, Hawaii, since 1958. There has been a consistent increase since monitoring began.



Watch **SmartFigure: The Mauna Loa CO_2 Record**

Most atmospheric scientists agree that increased carbon dioxide concentrations have contributed to a warming of Earth's atmosphere over the past several decades and will continue to do so in the decades to come. The magnitude of such temperature changes is uncertain and depends partly on the quantities of CO_2 contributed by human activities in the years ahead. The role of carbon dioxide in the atmosphere and its possible effects on climate are examined in more detail in Chapters 2 and 14.

Water Vapor

You are probably familiar with the term *humidity* from watching weather reports on TV. *Humidity* refers to the amount of water vapor in the air. As you will learn in Chapter 4, there are several ways to express humidity. The amount of water vapor in the air varies considerably, from practically none to up to about 4 percent by volume. Why is such a small fraction of the atmosphere so significant? The fact that water vapor is the source of all clouds and precipitation would be enough to explain its importance. However, water vapor has other roles. Like carbon dioxide, water vapor absorbs heat given off by Earth as well as some solar energy. It is therefore important when we examine the heating of the atmosphere and the movement of energy on Earth.

When water changes from one state to another (see Figure 4.3), it absorbs or releases heat. This energy is termed *latent heat*, which means "hidden heat." As we shall see in later chapters, water vapor in the atmosphere transports this latent heat from one region to another, and it is the energy source that helps drive many storms.

Aerosols

The movements of the atmosphere are sufficient to keep a large quantity of solid and liquid particles suspended within it. These tiny solid and liquid particles are collectively called **aerosols**. Although visible dust sometimes obscures the sky, these relatively large particles are too heavy to stay in the air very long. However, many particles are microscopic and remain suspended for considerable periods of time. They may originate from many sources, both natural and human made, and include sea salts from breaking waves, fine soil blown into the air, smoke and soot from fires, pollen and microorganisms lifted by the wind, ash and dust from volcanic eruptions, and more (Figure 1.17).

Figure 1.17 Aerosols

A. The satellite image shows two examples of aerosols. First, a large dust storm is blowing across northeastern China toward the Korean Peninsula. Second, a dense haze toward the south (bottom center) is human-generated air pollution. **B.** As the photo on the right shows, dust in the air can cause sunsets to be especially colorful.

Aerosols are most numerous in the lower atmosphere near their primary source, Earth's surface. Nevertheless, the upper atmosphere is not free of them: Some particles are carried to great heights by rising currents of air, while others are contributed by meteoroids that disintegrate as they pass through the atmosphere.

From a meteorological standpoint, these tiny, often invisible particles are important. First, many act as surfaces on which water vapor may condense, a critical function in the formation of clouds and fog. Second, aerosols can absorb or reflect incoming solar radiation. Thus, when an air pollution episode is occurring or when ash fills the sky following a volcanic eruption, the amount of sunlight reaching Earth's surface can be measurably reduced. Finally, aerosols contribute to an optical phenomenon we have all observed—the varied hues of red and orange at sunrise and sunset. The photo on the right in Figure 1.17 illustrates this phenomenon.

Ozone

Another important component of the atmosphere is **ozone**. It is a form of oxygen that contains three oxygen atoms in each molecule (O_3), unlike the oxygen we breathe, which has two atoms per molecule (O_2). There is very little ozone in the atmosphere; overall, it accounts for just 3 out of every 10 million molecules. Moreover, its distribution is not uniform. It is concentrated in a layer called the *stratosphere*, between 10 and 50 kilometers (6 and 31 miles) above the Earth's surface.

In this altitude range, oxygen molecules (O_2) are split into single atoms of oxygen (O) when they absorb ultraviolet radiation emitted by the Sun. Ozone is then created when a single atom of oxygen (O) and a molecule of oxygen (O_2) collide. This must happen in the presence of a third, neutral molecule that acts as a *catalyst* by allowing the reaction to take place without itself being consumed in the process. Ozone is concentrated in the 10- to 50-kilometer height range because a crucial balance exists there: The ultraviolet radiation from the Sun is sufficient to produce single atoms of oxygen, and enough gas molecules are present to bring about the required collisions.

The presence of this ozone layer in our atmosphere is essential to those of us who are land dwellers. The reason is that ozone absorbs much of the potentially harmful ultraviolet (UV) radiation from the Sun. If ozone did not filter a great deal of the ultraviolet radiation, land areas on our planet would be uninhabitable for most life as we know it. Thus, anything that reduces the amount of ozone in the atmosphere could affect the well-being of life on Earth. Just such a problem is described in Box 1.2.

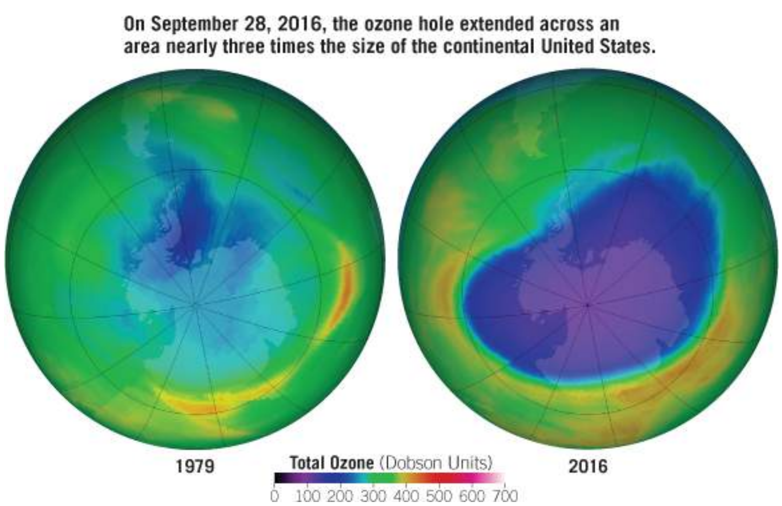
Box 1.2

Ozone Depletion: A Global Issue

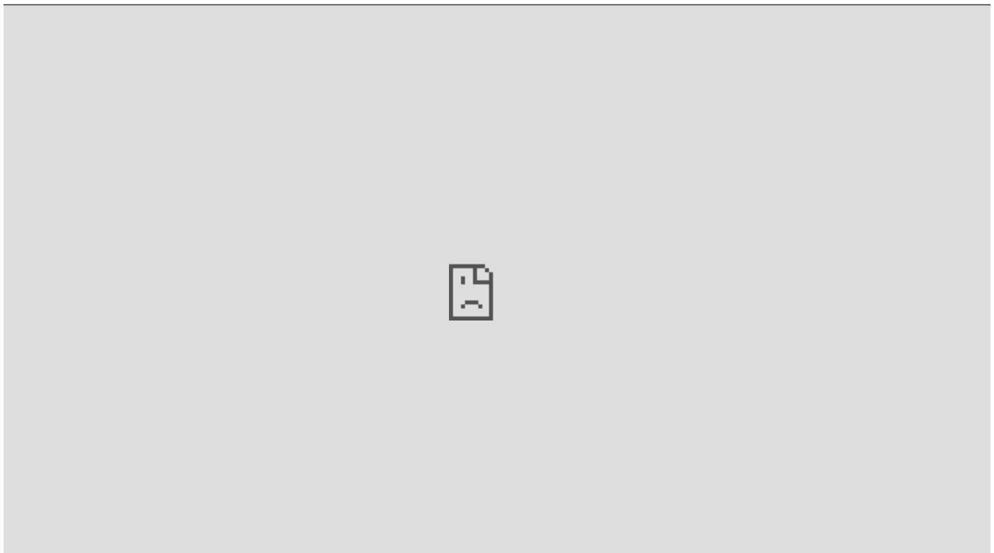
Although stratospheric ozone is concentrated high above Earth's surface, it is vulnerable to human activities. Manufactured chemicals break up ozone molecules in the stratosphere, weakening our shield against UV rays. Measurements over the past three decades confirm that ozone depletion is occurring worldwide and is especially pronounced above Earth's poles. Figure 1.B shows this effect over the South Pole.

Smartfigure 1.B Antarctic ozone hole

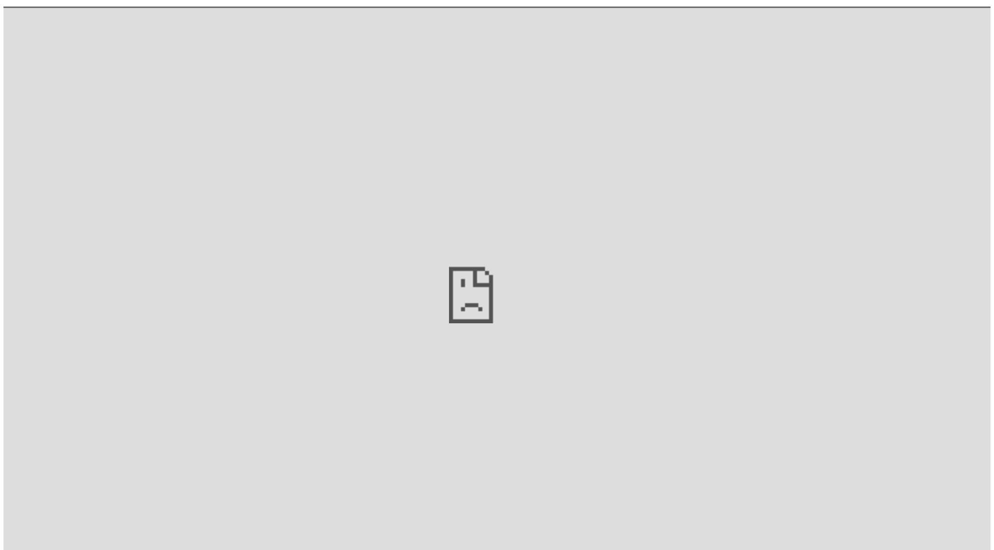
The two satellite images show ozone distribution in the Southern Hemisphere on the days in September 1979 and 2016 when the ozone hole was largest. The purple and blue colors are where there is the least ozone, and the yellows and reds are where there is more ozone.



Watch **SmartFigure: The Ozone Hole**



Watch **Animation: The Ozone Hole**



Over the past 80 years, people have unintentionally placed the ozone layer in jeopardy by polluting the atmosphere. The most significant of the offending chemicals are known as *chlorofluorocarbons (CFCs)*. Developed in the 1930s, CFCs were used as coolants for air-conditioning and refrigeration equipment, cleaning solvents, and propellants for aerosol sprays.

Because CFCs are practically inert (not chemically active) in the lower atmosphere, some of these gases gradually make their way up to the ozone layer, where sunlight separates the CFCs into their constituent atoms. The release of a single chlorine atom, which acts as a catalyst, can be responsible for destroying thousands of ozone molecules.

Because ozone filters out most of the UV radiation from the Sun, a decrease in atmospheric ozone permits more of these harmful wavelengths to reach Earth's surface. UV radiation's most serious threat to human health is an increased risk of skin cancer. Increased UV radiation can also impair the human immune system and promote cataracts, a clouding of the eye lens that reduces vision and may cause blindness if not treated.

In response to this problem, an international agreement known as the *Montreal Protocol* was developed in 1987 to eliminate the production and use of CFCs. More than 190 nations eventually ratified the treaty. Although relatively strong action has been taken, CFC levels in the atmosphere will not drop rapidly. Once CFC molecules are in the atmosphere, they can take many years to reach the ozone layer, and once there, they can remain active for decades. This does not promise a near-term reprieve for the ozone layer. Nevertheless, the Montreal Protocol represents a positive international response to solve this global problem.

Apply What You Know

1. What are CFCs, and what is their connection to ozone depletion?
2. What is the Montreal Protocol, and what did it achieve?

You might have wondered . . .

Isn't ozone some sort of pollutant?

■ Although the naturally occurring ozone in the stratosphere is critical to life on Earth, it is considered a pollutant when produced at ground level because it can damage vegetation and harm human health. Ozone is a major component in a noxious mixture of gases and particles called *photochemical smog* formed from pollutants emitted by motor vehicles and industries.

Concept Checks 1.4

■ What are the two major components of clean, dry air? What proportion does each represent?

■ Why is carbon dioxide an important component of Earth's atmosphere? Why are water vapor and aerosols important atmospheric constituents?

■ What is ozone? Why is ozone important to life on Earth?

1.5 Vertical Structure of the Atmosphere

LO 5 Interpret a graph that shows changes in air pressure from Earth's surface to the top of the atmosphere. Sketch and label a graph that shows the thermal structure of the atmosphere.

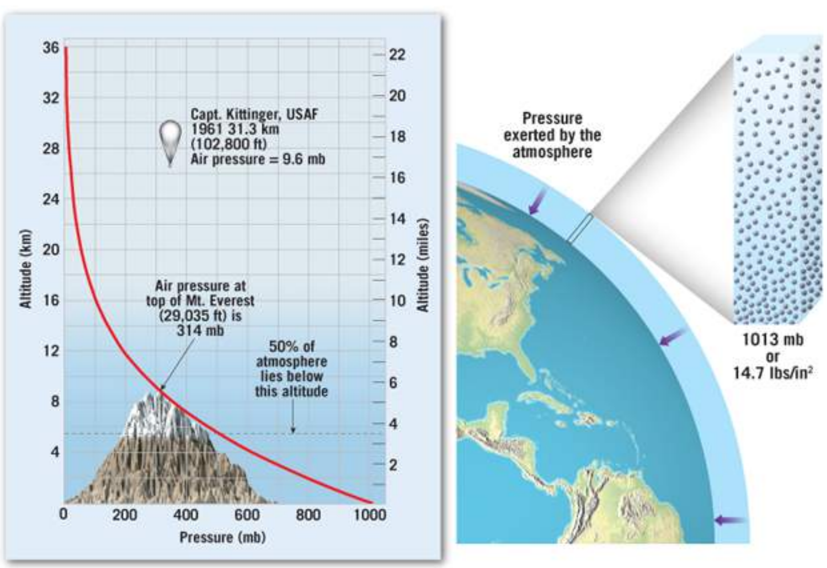
When compared to the size of the solid Earth, the envelope of air surrounding our planet is indeed very shallow. To say that the atmosphere begins at Earth's surface and extends upward is obvious. However, where does the atmosphere end, and where does outer space begin? There is no sharp boundary; the atmosphere rapidly thins as you travel away from Earth, until there are too few gas molecules to detect.

Pressure Changes

To understand the vertical extent of the atmosphere, let us examine the changes in atmospheric pressure with height. Atmospheric pressure is simply the weight of the air above. To describe atmospheric pressure, the National Weather Service uses a measure called the *millibar* (mb), which will be discussed in detail in Chapter 6. At sea level, the average pressure is slightly more than 1000 millibars. This corresponds to a weight of about 14.7 pounds per square inch. Obviously, the pressure at higher altitudes is less because there is less air (fewer air molecules) above these altitudes (Figure 1.18).

Figure 1.18 Air pressure changes with altitude

The rate of pressure decrease with an increase in altitude is not constant. Pressure decreases rapidly near Earth's surface and more gradually at greater heights. Put another way, the figure shows that the vast bulk of the gases making up the atmosphere is near Earth's surface and that the gases gradually merge with the emptiness of space.



> Atmospheric pressure is simply the weight of the air above.

One-half of the atmosphere lies below an altitude of 5.6 kilometers (3.5 miles). At about 16 kilometers (10 miles), 90 percent of the atmosphere has been traversed. At an altitude of 100 kilometers, the atmosphere is so thin that the density of air is less than could be found in the most perfect artificial vacuum at the surface. Nevertheless, the atmosphere continues to even greater heights. In fact, traces of our atmosphere extend for thousands of kilometers beyond Earth's surface. Thus, to say where the atmosphere ends and outer space begins is arbitrary and depends on what phenomenon one is studying. It is apparent that there is no sharp boundary.

The graphic portrayal of pressure data in Figure 1.18 shows that the rate of pressure decrease is not constant. Rather, air pressure falls at a decreasing rate with an increase in altitude. Put another way, air is highly compressible—that is, the gases that make up air expand with decreasing pressure and become compressed with increasing pressure.

Eye on the Atmosphere 1.1

This jet is cruising at an altitude of 10 kilometers (6.2 miles).

Apply What You Know

1. Refer to the graph in Figure 1.18. What is the approximate air pressure where the jet is flying?
2. About what percentage of the atmosphere is below the jet (assuming that the pressure at the surface is 1000 millibars)?

Temperature Changes

By the early twentieth century, scientists collecting data obtained from balloons and kites found that the air temperature dropped with increasing height above Earth's surface. This phenomenon is felt by anyone who has climbed a high mountain and is obvious in pictures of snow-capped mountaintops rising above snow-free lowlands (Figure 1.19).

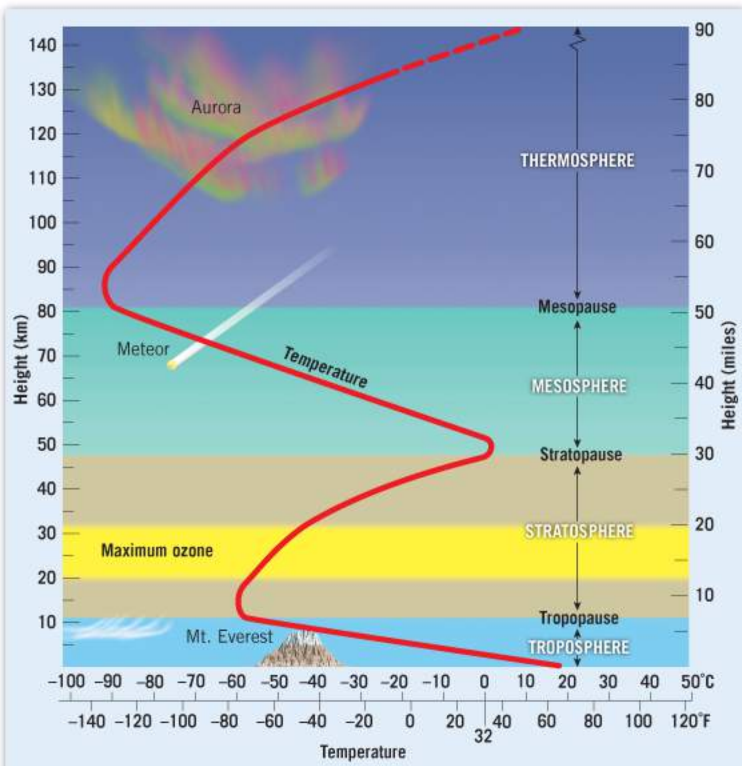
Figure 1.19 Temperature change in the troposphere

Snow-capped mountains and snow-free lowlands are a reminder that temperatures decrease as we go higher in the troposphere.

Scientists once believed that the temperature continued to decrease with height to a value of absolute zero (−273°C) at the outer edge of the atmosphere. In 1902, however, French scientist Leon Philippe Teisserenc de Bort refuted the notion that temperature decreases continuously with an increase in altitude. In studying the results of more than 200 balloon launchings, Teisserenc de Bort found that the temperature leveled off at an altitude between 8 and 12 kilometers (5 and 7.5 miles). Later, the use of balloons and rocket-sounding techniques revealed the temperature structure of the atmosphere up to great heights. Based on these temperature measurements, the atmosphere can be divided vertically into four layers (Figure 1.20). The temperature profile shown in Figure 1.20 represents the average temperature change with altitude. However, the actual temperature profile can be quite variable from one day to the next—particularly in the lower atmosphere.

Figure 1.20 Thermal structure of the atmosphere

Earth's atmosphere is traditionally divided into four layers, based on temperature.



Troposphere

The bottom layer in which we live, where average temperatures decrease with an increase in altitude, is the **troposphere**. The term was coined in 1908 by Teisserenc de Bort and literally means the region where air “turns over,” a reference to the appreciable vertical mixing of air in this lowermost zone.

The temperature decrease in the troposphere is called the **environmental lapse rate**. Its average value is 6.5°C per kilometer (3.5°F per 1000 feet), a figure known as the *normal lapse rate*. It should be emphasized, however, that the environmental lapse rate is not a constant but rather can be highly variable and must be regularly measured. Radiosondes are used to measure the actual environmental lapse rate, as well as gather information about vertical changes in air pressure, wind, and humidity. A **radiosonde** is an instrument package that is attached to a balloon and transmits data by radio as it ascends through the atmosphere (Figure 1.21). The environmental lapse rate can vary over the course of a day as a result of fluctuations in weather, as well as seasonally and from place to place. Sometimes shallow layers where temperatures actually increase with height are observed in the troposphere. Such reversals, called **temperature inversions**, are described in greater detail in Chapter 13.

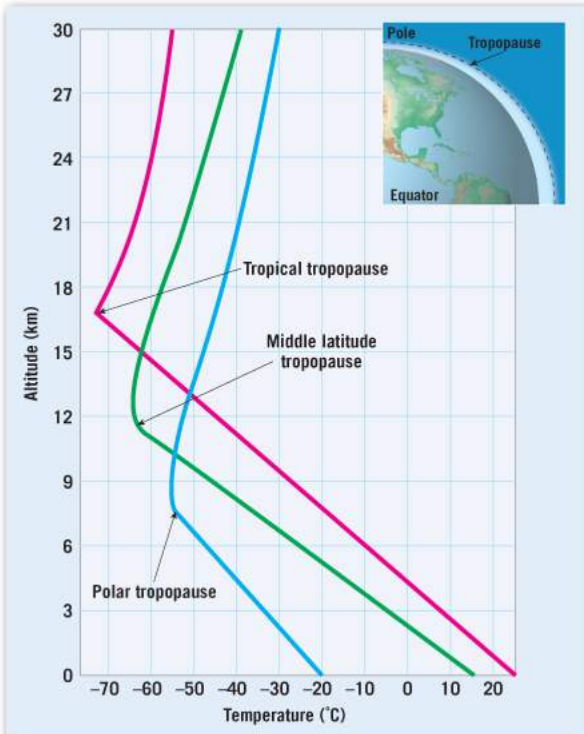
Figure 1.21 Radiosonde

This lightweight package of instruments is carried aloft by a small weather balloon. It transmits data on vertical changes in temperature, pressure, and humidity in the troposphere. The troposphere is where practically all weather phenomena occur, so it is very important to have frequent measurements.

The temperature continues to decrease to an *average* height of about 12 kilometers (7.5 miles), which marks the top of the troposphere, called the **tropopause** (see Figure 1.20). Yet the thickness of the troposphere is not the same everywhere. In the tropics, the tropopause reaches heights in excess of 16 kilometers (10 miles), whereas in polar regions it is lower, varying from about 7 to 8 kilometers (about 5 miles) (Figure 1.22). Warm surface temperatures and highly developed thermal mixing as the warmed air rises are responsible for the greater vertical extent of the troposphere near the equator.

Figure 1.22 **Differences in the height of the tropopause**

The variation in the height of the tropopause, as shown on the small inset diagram, is greatly exaggerated.



The troposphere is the chief focus of meteorologists because it is in this layer that essentially all important weather phenomena occur. Almost all clouds and certainly all precipitation, as well as all our violent storms, are born in this lowermost layer of the atmosphere. This is why the troposphere is often called the "weather sphere."

> The atmosphere is divided into four layers, based on temperature—the *troposphere*, *stratosphere*, *mesosphere*, and *thermosphere*.

Stratosphere

Above the troposphere lies the **stratosphere**. In the stratosphere, the temperature at first remains nearly constant to a height of about 20 kilometers (12 miles) before it begins a sharp increase that continues until the **stratopause** is encountered at a height of about 50 kilometers (30 miles) above Earth's surface (see Figure 1.20). The high concentration of ozone in the stratosphere accounts for the rise in temperature observed in this layer. Recall that ozone absorbs ultraviolet radiation from the Sun, which in turn causes its temperature to rise.

Although the troposphere is dominated by large-scale turbulence and mixing, very little vertical mixing occurs in the stratosphere. This is because the stratosphere experiences a temperature inversion, where cold air lies beneath warm air, in contrast to the opposite occurrence in the troposphere.

Mesosphere

In the third layer, the **mesosphere**, temperatures decrease with height until the **mesopause**, or top of the mesosphere, is reached (see Figure 1.20). This decrease in temperature with height leads to abundant vertical mixing. The mesopause is located about 80 kilometers (50 miles) above the surface, where the average temperature approaches a chilly −90°C (−130°F)—the coldest temperatures anywhere in the atmosphere.

The mesosphere is one of the least explored regions of the atmosphere because it cannot be reached by the highest-flying airplanes and research balloons, nor is it accessible to the lowest-orbiting satellites. Recent technical developments are just beginning to fill this knowledge gap.

Thermosphere

The fourth layer extends outward from the mesopause and has no well-defined upper limit. It is the **thermosphere**, a layer that contains only a tiny fraction of the atmosphere's mass. In the extremely rarified air of this outermost layer, temperatures again increase as oxygen and nitrogen atoms absorb very shortwave, high-energy solar radiation (Figure 1.20).

Temperatures rise to extremely high values of more than 1000°C (1800°F) in the thermosphere. But such temperatures are not comparable to those experienced near Earth's surface. **Temperature** is defined in terms of the average speed at which molecules move—the higher the speed, the higher the temperature. Because the gases of the thermosphere are moving at very high speeds, the temperature is very high. But the gases are so sparse that collectively they possess only an insignificant quantity of thermal energy (heat). For this reason, the temperature of a satellite orbiting Earth in the thermosphere is determined chiefly by the amount of solar radiation it absorbs, and not by the high temperature of the almost nonexistent surrounding air. If an astronaut inside were to expose his or her hand, the air in this layer would not feel hot.

The Ionosphere

In addition to the layers defined by vertical variations in temperature, scientists recognize another layer in the atmosphere. Located between 80 and 400 kilometers (50 to 250 miles) above Earth’s surface, and thus coinciding with the lower portion of the thermosphere, is an electrically charged layer known as the **ionosphere**. Here molecules of nitrogen and atoms of oxygen are readily ionized as they absorb high-energy shortwave solar radiation. Ionization is a process in which the affected molecule or atom loses one or more electrons and becomes a positively charged ion, and the electrons set free then travel as electric currents.

Eye on the Atmosphere 1.2

When this weather balloon was launched, the surface temperature was 17°C. It is now at an altitude of 1 kilometer.

Apply What You Know

1. What term is applied to the instrument package being carried aloft by the balloon?
2. In what layer of the atmosphere is the balloon?
3. If average conditions prevail, what air temperature is the instrument package recording? How did you figure this out?

As best we can tell, the ionosphere has little impact on our daily weather. But this layer of the atmosphere is the site of one of nature's most interesting spectacles, the **auroras** (Figure 1.23). The *aurora borealis* (northern lights) and its Southern Hemisphere counterpart, the *aurora* *australis* (southern lights), appear in a wide variety of forms. Sometimes the displays consist of vertical streamers in which there can be considerable movement. At other times, the auroras appear as a series of luminous expanding arcs or as a quiet glow that has an almost foglike quality.

Figure 1.23 The auroras

The aurora borealis (northern lights), as seen in Alaska. The same phenomenon occurs toward the South Pole, where it is called the aurora australis (southern lights).

Auroral displays are aligned with Earth's magnetic poles and closely correlated with large solar storms, such as solar flares. Solar flares are massive magnetic storms on the Sun that emit enormous quantities of fast-moving atomic particles. As these charged particles (ions) approach Earth, they are captured by its magnetic field, which in turn guides them toward the magnetic poles. Then, as the ions impinge on the ionosphere, they energize the atoms of oxygen and molecules of nitrogen and cause them to emit light—the glow of the auroras. Because the occurrence of solar storms is closely associated with sunspot activity, auroral displays increase conspicuously at times when sunspots are most numerous.

Concept Checks 1.5

- Does air pressure increase or decrease with an increase in altitude? Is the rate of change constant or variable? Explain.
- The atmosphere is divided vertically into four layers based on temperature. List these layers in order from lowest to highest. In which layer does practically all weather occur?
- What is the *ionosphere*? How is it related to the auroras?

Concepts in Review

1.1 Focus on the Atmosphere

LO 1 Distinguish between weather and climate, name the basic elements of weather and climate, and list several important atmospheric hazards.

Key Terms

meteorology

weather

climate

- Meteorology is the scientific study of the atmosphere. *Weather* refers to the state of the atmosphere at a given time and place. It is constantly changing, sometimes from hour to hour. *Climate* refers to the average weather conditions and the sum of all statistical weather information that helps describe a place or region.
- The most important elements of weather and climate are (1) air temperature, (2) humidity, (3) type and amount of cloudiness, (4) type and amount of precipitation, (5) air pressure, and (6) the speed and direction of the wind.
- Some atmospheric hazards are storm related, such as lightning, blizzards, and hail. Others are not storm related, such as fog, heat waves, and drought.

1.2 The Nature of Scientific Inquiry

LO 2 Discuss the nature of scientific inquiry, including the construction of hypotheses and the development of theories.

Key Terms

hypothesis

theory

- All science is based on the assumption that the natural world behaves in a consistent and predictable manner. Scientists make careful observations, construct tentative explanations for those observations (hypotheses), and then test those hypotheses with field investigations and laboratory work.
- In science, a theory is a well-tested and widely accepted explanation that the scientific community agrees best fits certain observable facts.

1.3 Earth as a System

LO 3 List and describe Earth's four major spheres. Define *system*, and explain why Earth is considered a system.

Key Terms

atmosphere

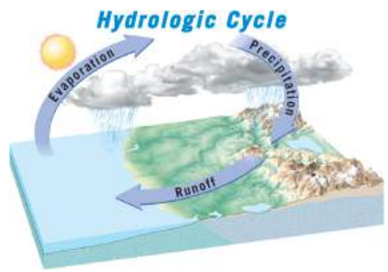
hydrosphere

lithosphere

biosphere

system

- Earth's physical environment is traditionally divided into three major parts: Earth's gaseous envelope, called the atmosphere; the water portion of our planet, called the hydrosphere; and the solid Earth, called the lithosphere. A fourth Earth sphere is the biosphere, the totality of life on Earth.
- Although each of Earth's four spheres can be studied separately, they are all related in a complex and continuously interacting whole that is called the Earth system.
- Earth system science uses an interdisciplinary approach to integrate the knowledge of several academic fields in the study of our planet and its global environmental problems.
- The two sources of energy that power the Earth system are (1) the Sun, which drives the external processes that occur in the atmosphere, hydrosphere, and at Earth's surface, and (2) heat from Earth's interior that powers the internal processes that produce volcanoes, earthquakes, and mountains.


Hydrologic Cycle
Evaporation
Precipitation
Runoff

1.4 Composition of the Atmosphere

LO 4 List the major gases composing Earth's atmosphere and identify the components that are most important meteorologically.

Key Terms

air

aerosols

ozone

- Air is a mixture of many discrete gases, and its composition varies from time to time and place to place. Two nonvariable gases, nitrogen and oxygen, make up 99 percent of the volume of the atmosphere.
- Carbon dioxide (CO_2), a variable gas present in only minute amounts, is an efficient absorber of energy emitted by Earth and thus influences the heating of the atmosphere.
- Water vapor is important because it is the source of all clouds and precipitation. Like carbon dioxide, water vapor can absorb heat emitted by Earth. In the atmosphere, water vapor transports latent ("hidden") heat from place to place and is the energy that helps to drive many storms.
- Aerosols are tiny solid and liquid particles that are important because they may act as surfaces onto which water vapor can condense. They also absorb and reflect incoming solar radiation.
- Ozone, a form of oxygen that combines three oxygen atoms into each molecule (O_3), is a gas concentrated in the stratosphere. Ozone is important to life because it can absorb harmful ultraviolet radiation from the Sun. People have placed Earth's ozone layer in jeopardy by polluting the atmosphere with chlorofluorocarbons (CFCs), which break apart the ozone.

1.5 Vertical Structure of the Atmosphere

LO 5 Interpret a graph that shows changes in air pressure from Earth's surface to the top of the atmosphere. Sketch and label a graph that shows the thermal structure of the atmosphere.

Key Terms

troposphere

environmental lapse rate

radiosonde

temperature inversion

tropopause

stratosphere

stratopause

mesosphere

mesopause

thermosphere

temperature

ionosphere

aurora

- Pressure is the weight of the air above a location. Because air is compressible, pressure decreases at an increasing rate as you go up in the atmosphere.
- Based on temperature, the atmosphere is divided vertically into four layers. The troposphere is the lowermost layer. In the troposphere, temperature usually decreases with increasing altitude. Essentially, all important weather phenomena occur in the troposphere.
- Above the troposphere is the stratosphere, which warms with altitude because of absorption of UV radiation by ozone. In the mesosphere, temperatures again decrease. Upward from the mesosphere is the

thermosphere, a layer with only a tiny fraction of the atmosphere's mass and no well-defined upper limit.

- The ionosphere is an electrically charged layer of the atmosphere where molecules of nitrogen and atoms of oxygen are readily ionized as they absorb solar radiation.
- Auroras (the northern and southern lights) occur within the ionosphere. Auroras form as atomic particles ejected from the Sun during solar flare activity enter the atmosphere near Earth's magnetic poles and energize the atoms of oxygen and molecules of nitrogen, causing them to emit light.

Exercises and Online Activities

Mastering Meteorology™

For instructor-assigned homework, test prep resources, and other learning materials, visit **Mastering Meteorology.**

Review Questions

1. What is meteorology?
2. List some examples of how weather changes.
3. Explain how climate changes.
4. What are some examples of atmospheric hazards?
5. What is a hypothesis? How is a theory different from a hypothesis?
6. Why is the scientific method useful?
7. List the four spheres of Earth, and describe their basic characteristics.
8. How much of Earth's surface is covered by oceans?
9. Briefly explain why is Earth considered a "system."
10. Sketch and describe the hydrologic cycle.
11. List the components of Earth's atmosphere, and indicate which ones are variable.
12. In what ways is water vapor important in the atmosphere?
13. What are aerosols, and what role do they play in the atmosphere?
14. Why is ozone important in the atmosphere?
15. Define *atmospheric pressure*.
16. How does pressure change vertically in the atmosphere?
17. Sketch the typical vertical temperature profile of the atmosphere, and label each layer. List their basic properties.
18. Explain why temperature increases in the stratosphere.
19. How is the ionosphere different from the atmosphere's thermal layers?
20. Explain how an aurora is formed.

Give It Some Thought

1. Determine which statements refer to weather, and which are considered climate.

a. The baseball game was rained out today.

b. January is Chicago's coldest month.

c. North Africa is a desert.

d. Light rain fell most of the afternoon.

e. Last evening a tornado ripped through central Oklahoma.

f. I am moving to southern Arizona because it is warm and sunny.

g. Thursday's low of −20°C is the coldest temperature ever recorded for that city.

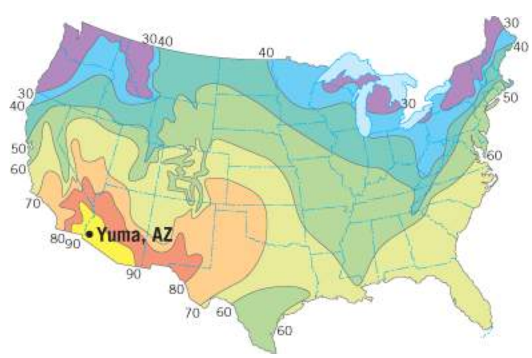
h. It is partly cloudy.

2. This map shows the mean percentage of sunshine received in the month of November across the 48 contiguous United States.

a. Does this map relate more to weather or to climate?

b. If you were to visit Yuma, Arizona, on a day in November, would you *expect* to experience a sunny day or an overcast day?

c. Might what you actually experience during your visit differ from what you expected? Explain.



3. Briefly explain this statement in your own words: "Climate is what you expect; weather is what you get."

4. After entering a dark room, you turn on a wall switch, but the light does not come on. Suggest at least three hypotheses that might explain this observation.

5. Where would you expect the thickness of the troposphere (that is, the distance between Earth's surface and the tropopause) to be greater: over Hawaii or over Alaska? Why? Do you think it is likely that the thickness of the troposphere over Alaska is different in January from in July? If so, why?

6. Making accurate measurements and observations is a basic part of scientific inquiry. The accompanying radar image, showing the distribution and intensity of precipitation associated with a strong winter storm, provides one example. Identify two additional images in this chapter that illustrate ways in which scientific data are gathered, and briefly describe each.

7. Determine which layer(s) of the atmosphere is/are best described by each statement below. Some statements have more than one answer!

a. This layer is a temperature inversion.

b. This layer contains most of the ozone.

c. This layer contains all of Earth's weather.

d. This layer has lots of vertical mixing.

e. This layer has little or no vertical mixing.

8. The accompanying photo provides an example of interactions among different parts of the Earth system. It is a view of a landslide triggered by extraordinary rains in March 2014. Which of Earth's four "spheres" were involved in this natural disaster that buried a 1-square-mile rural neighborhood near Oso, Washington, and caused more than 40 fatalities? Describe how each contributed to the mudflow.

By the Numbers

1. Refer to the weather map in Figure 1.3 to answer the following:
    - a. Estimate the predicted high temperatures in central New York State and the northwestern corner of Arizona.
    - b. Where is the coldest area on the weather map? Where is the warmest?
    - c. On this weather map, H stands for the center of a region of high pressure. Does high pressure appear to be associated with precipitation or with fair weather?
    - d. Which is warmer—central Texas or central Maine? Would you normally expect this to be the case?
2. Refer to the graph in Figure 1.4 to answer the following questions about temperatures in New York City:
    - a. What is the approximate average daily high temperature in January? In July?
    - b. Approximately what are the highest and lowest temperatures ever recorded?
3. Refer to the graph in Figure 1.6. Which year had the greatest number of billion-dollar weather disasters? How many events occurred that year? In which year was the total damage amount highest?
4. Refer to the graph in Figure 1.18 to answer the following:
    - a. Approximately how much does the air pressure drop (in millibars) between the surface and 4 kilometers (2.5 miles)? (Use a surface pressure of 1000 millibars.)
    - b. How much does the pressure drop between 4 and 8 kilometers (2.5 and 5 miles)?
    - c. Based on your answers to parts a and b, select the correct answer: With an increase in altitude, air pressure decreases at a(n) (constant, increasing, decreasing) rate.

d. If you were to climb to the top of Mount Everest, how many breaths of air would you have to take at that altitude to equal one breath at sea level?

e. If you are flying in a commercial jet at an altitude of 12 kilometers (7.5 miles), about what percentage of the atmosphere's mass is below you?

5. If the temperature at sea level were 23°C, what would the air temperature be at a height of 2 kilometers, under average conditions?

6. Use the graph of the atmosphere's thermal structure (Figure 1.20) to answer the following:

a. What are the approximate height and temperature of the stratopause?

b. At what altitude is the temperature lowest? What is the temperature at that height?

7. Answer the following questions by examining the graph in Figure 1.22:

a. In which one of the three regions (tropics, middle latitudes, poles) is the *surface* temperature lowest?

b. In which region is the tropopause encountered at the lowest altitude? The highest? What are the altitudes and temperatures of the tropopause in those regions?

8. On a spring day, a middle-latitude city (about 40° north latitude) has a surface (sea-level) temperature of 10°C.

a. If vertical soundings on this spring day reveal a nearly constant environmental lapse rate of 6.5°C per kilometer and a temperature at the tropopause of –55°C, what is the height of the tropopause?

b. On the same spring day, a station near the equator has a surface temperature of 25°C, which is 15°C higher than the middle-latitude city mentioned in part a. Vertical soundings reveal an environmental lapse rate of 6.5°C per kilometer and indicate that the tropopause is encountered at 16 kilometers. What is the air temperature at the tropopause?

Beyond the Textbook

1. Exploring the Ideal Gas Law

The following definitions will assist you as you complete this exercise: *pressure* = how much the molecules push on the sides of the box; *volume* = the size of the box; *density* = how closely packed the molecules are; and *temperature* = average speed of the molecules.

For this activity, there are two options. One is Flash-based (iPads and iPhones won't run Flash) and the other is Java-based (Chrome won't run Java, but the other browsers will). Choose whichever format works for your technology.

To Run the Flash-Based Simulation:

Open the Gas Law Simulator located at http://ch301.cm.utexas.edu/section2.php?target=gases/kmt/gas-simulator.html, and click on the picture.

- Change volume by using the *up and down arrows*. You can keep the volume constant by clicking on the *lock icon*.
- Change temperature by clicking on either the *heat knob* or the *cool knob*.
- Add molecules by moving the *pump handle* on the bicycle pump. (Use only one gas, A or B.)
- Remove molecules by clicking on the *yellow valve* below the pressure indicator.

To Run the Java-Based Simulation:

Go to http://phet.colorado.edu/en/simulation/legacy/gas-properties, and download the Java program. You will need to give permission to run the program. (Be sure your Java is up to date!)

- Change volume by moving the *person* to the left of the box.
- Change temperature by moving the *heat control* up or down.
- Add molecules by moving the *pump handle*. (Use only one gas.)
- Remove molecules by *moving the lid* on top of the box to the left and right.

Activity A. First, you will explore how temperature and the number of molecules determine the pressure when the *volume is constant* (in other words, the size of the box does not change).

1. How does the pressure change when you *increase the temperature*?
2. How does the pressure change when you *decrease the temperature*?
3. How does the pressure change when you *increase the number of molecules*?
4. How does the pressure change when you *decrease the number of molecules*?

Activity B. Next, you will explore how temperature and the number of molecules determine the volume when you have a *fixed pressure*. Remember, for this experiment you are keeping the pressure *constant*. In other words, for each variable you change, you must modify the volume to put pressure back to its original value. (Use only one "pump" of molecules for questions 5 and 6.)

5. How does the volume need to change when you increase the temperature to get pressure back to its original value?

6. How does the volume have to change when you decrease the temperature to get pressure back to its original value?

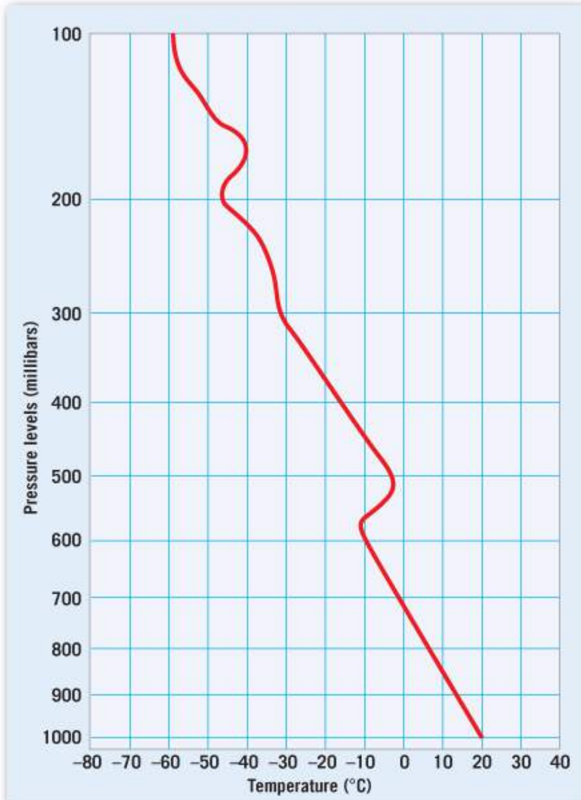
For questions 7 and 8: If you are using the Java-based simulation, you will need to click the radial button next to *temperature* in the Constant Parameter section at the top right-hand corner of the window.

7. How does the volume need to change when you increase the number of molecules to 2 "pumps" to get pressure back to its original value?
8. How does the volume have to change when you decrease the number of molecules to get pressure back to its original value?

2. Exploring a Temperature Profile

The accompanying diagram shows a simplified temperature profile of a portion of the atmosphere. (Temperature profiles are usually obtained twice each day from radiosondes at numerous locations around the world.) Use this diagram to answer the following questions.

1. What is the temperature (solid red line) at the surface (pressure = 1000 millibars)?
2. What is the temperature at the 600-mb pressure level?
3. What is the temperature at the 250-mb pressure level?
4. Circle each of the inversions on the temperature profile. Recall that a temperature inversion is a region where temperature *increases* with height.
5. Does this graph look like the average temperature profile shown in Figure 1.20 in your textbook? How is it different?
6. What layer of Earth's atmospheric is shown on this graph?



Pressure levels (millibars)
100
200
300
400
500
600
700
800
900
1000
−80 −70 −60 −50 −40 −30 −20 −10 0 10 20 30 40
Temperature (°C)

Chapter 2 Heating Earth's Surface and Atmosphere

Weather is the result of the interactions of solar radiation with Earth's atmosphere and its land-sea surface.

Focus on Concepts

Each statement represents the primary learning objective for the corresponding major heading within the chapter. After you complete the chapter, you should be able to:

1. Explain what causes the Sun angle and length of daylight to change throughout the year. Describe how these changes result in seasonal changes in temperature (2.1).
2. Describe the different forms of energy and heat in the atmosphere: kinetic energy, potential energy, latent heat, and sensible heat (2.2).
3. List and describe the three mechanisms of heat transfer (2.3).
4. Describe what happens to incoming solar radiation (2.4).
5. Explain how the greenhouse effect works and why it is important (2.5).
6. Describe the major components of Earth's annual energy budget (2.6).

From our everyday experiences, we know that the Sun's rays feel warmer and paved roads become much hotter on clear, sunny days than on overcast days. Pictures of snowcapped mountains remind us that temperatures decrease with altitude. And we know that the fury of winter is always replaced by the newness of spring. What many don't know is that these are manifestations of the same phenomena that causes the blue color of the sky and the red color of a brilliant sunset. All are results of the interaction of solar radiation with Earth's atmosphere and its land–sea surface.

2.1 Earth–Sun Relationships

LO 1 Explain what causes the Sun angle and length of daylight to change throughout the year. Describe how these changes result in seasonal changes in temperature.

The amount of solar energy received at any location varies with latitude, time of day, and season of the year. Contrasting images of polar bears on ice floes with palm trees along a tropical beach serve to illustrate the extremes. The unequal heating of Earth's surface creates winds and drives ocean currents, which in turn transport heat from the tropics toward the poles in an unending attempt to balance energy inequalities.

The consequences of these processes are the phenomena we call *weather*. If the Sun were "turned off," global winds and ocean currents would quickly cease. Yet as long as the Sun shines, winds *will* blow and weather *will* persist. So, to understand how the dynamic weather machine works, we must understand why different latitudes receive different quantities of solar energy and why the amount of solar energy received changes during the course of a year to produce the seasons (Figure 2.1).

Figure 2.1 **An understanding of Earth–Sun relationships is basic to an understanding of the seasons**

A. Clear, warm summer day in Chicago, Illinois. **B.** Cold winter scene in Chicago.

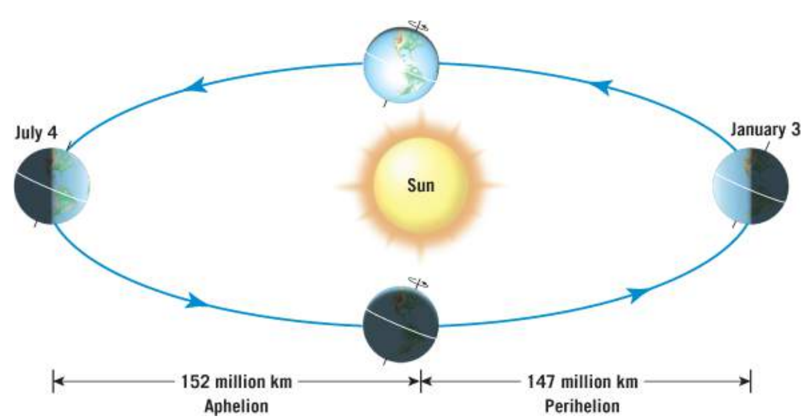
Earth's Rotation and Orbit

Earth has two basic motions—its rotation (*spin*) on its axis and its annual orbit (or *revolution*) around the Sun. **Rotation**, the spinning of Earth on its axis, which is an imaginary line connecting the North Pole to the South Pole, takes 24 hours (1 day) and produces the cycle of day and night.

Earth also moves in a slightly elliptical **orbit** around the Sun that takes about 365¼ days (1 year). Because Earth's orbit is not perfectly circular, the distance varies during the year (Figure 2.2). Each year, on about January 3, our planet is about 147 million kilometers (91.5 million miles) from the Sun, closer than at any other time—a position called **perihelion**. About 6 months later, on July 4, Earth is about 152 million kilometers (94.5 million miles) from the Sun, farther away than at any other time—a position called **aphelion**. The average distance between Earth and the Sun is about 150 million kilometers (93 million miles).

Figure 2.2 Earth's slightly elliptical orbit around the Sun

Notice that the Earth is farthest from the Sun on July 4 (aphelion) and closest to the Sun on January 3 (perihelion).



Although Earth is closest to the Sun and receives up to 7 percent more energy in January than in July, this difference plays only a minor role in producing seasonal temperature variations, as evidenced by the fact that Earth is closest to the Sun during the Northern Hemisphere winter.

> Earth's two basic motions are its 24-hour rotation on its axis and its year-long orbit around the Sun.

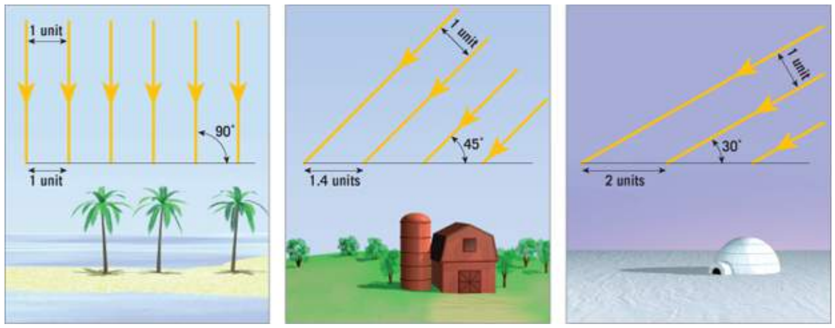
What Causes the Seasons?

If variations in the distance between the Sun and Earth do not cause seasonal temperature changes, what does? You have undoubtedly noticed that the *length of daylight* changes gradually throughout the year. This is more noticeable the further you get from the equator. In fact, at the North Pole, daylight is continuous from March 21 through August 21. This accounts for some of the differences in the temperatures experienced in summer versus winter: Longer daylight hours result in warmer days.

In addition, *the angle (altitude) of the Sun above the horizon affects the amount of solar energy that reaches Earth's surface*. When the Sun is directly overhead (at a 90° angle), the solar rays are most concentrated and thus most intense. At lower Sun angles, the rays become more spread out and less intense. This explains why tropical areas, which experience consistently higher Sun angles throughout the year, are much warmer than polar regions, where the Sun angles are lower (Figure 2.3). You have probably experienced this when using a flashlight. If the flashlight beam strikes a surface at a 90° angle, a small intense spot is produced. By contrast, if the beam strikes at any other angle, the area illuminated is larger—but noticeably dimmer.

Figure 2.3 Changes in the angle of the Sun’s rays cause variations in the amount of solar energy that reaches Earth’s surface

The higher the angle, the more intense the solar radiation reaching the surface. Notice in the last image that the same amount of solar energy is spread over twice the distance.



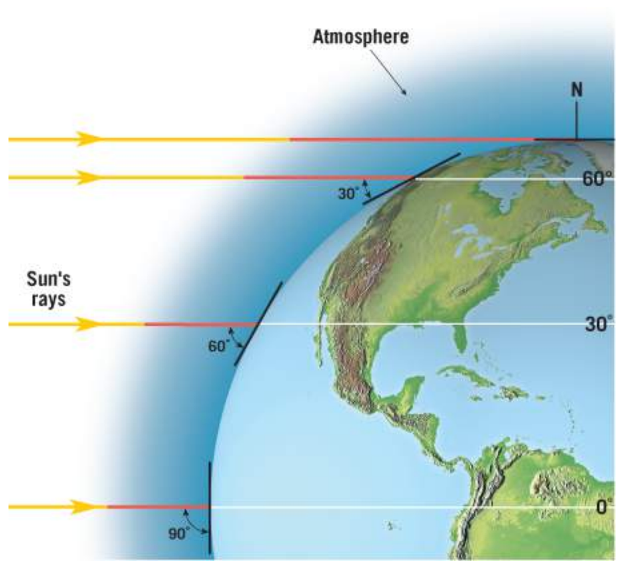
The angle at which the Sun strikes a location varies seasonally. For example, for someone living in Chicago, Illinois, the Sun is highest in the sky at noon on June 21–22. (Comparisons of seasonal changes in Sun angles are based on *noon solar time* because that is when the Sun is highest in the sky.) But as summer gives way to autumn, the noon Sun gradually appears lower in the sky, and sunset occurs earlier each evening as daylight hours decrease. The lowest noon Sun angle and earliest sunset in Chicago occur on December 21–22.

Although Chicago and other midlatitude cities in the Northern Hemisphere experience their shortest day and lowest Sun angle in late December, their lowest average temperatures are usually experienced a few weeks later, in January. The reason for this temperature lag will be discussed in Chapter 3.

Sun angle also determines the path that solar rays take as they pass through the atmosphere (Figure 2.4). When the Sun is directly overhead, the rays strike the atmosphere at a 90° angle and travel the shortest possible route to Earth’s surface. Rays entering the atmosphere at a 30° angle must travel twice this distance before reaching the surface, whereas rays entering at a 5° angle travel a distance roughly equivalent to 11 atmospheres. The longer the path the rays must travel, the greater the chance that sunlight will be dispersed (scattered) or absorbed by Earth's atmosphere, which reduces the intensity of sunlight reaching the surface. Changes in sun angle explain why noon is the brightest part of a clear day and why light dims as sunset approaches.

Figure 2.4 The amount of atmosphere sunlight must traverse before reaching the Earth's surface affects its intensity

Rays striking Earth at a low angle (near the poles) must traverse more of the atmosphere than rays striking at a high angle (around the equator) and thus are subject to greater depletion by reflection, scattering, and absorption.

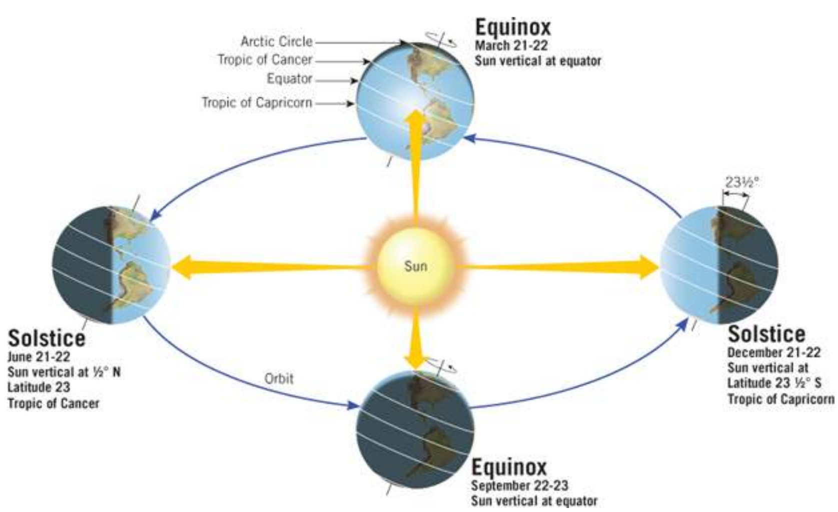


> Variations in the amount of solar energy reaching a location are caused primarily by seasonal changes in intensity of sunlight (which is determined by the angle at which the Sun's rays strike Earth's surface) and by changes in the length of daylight.

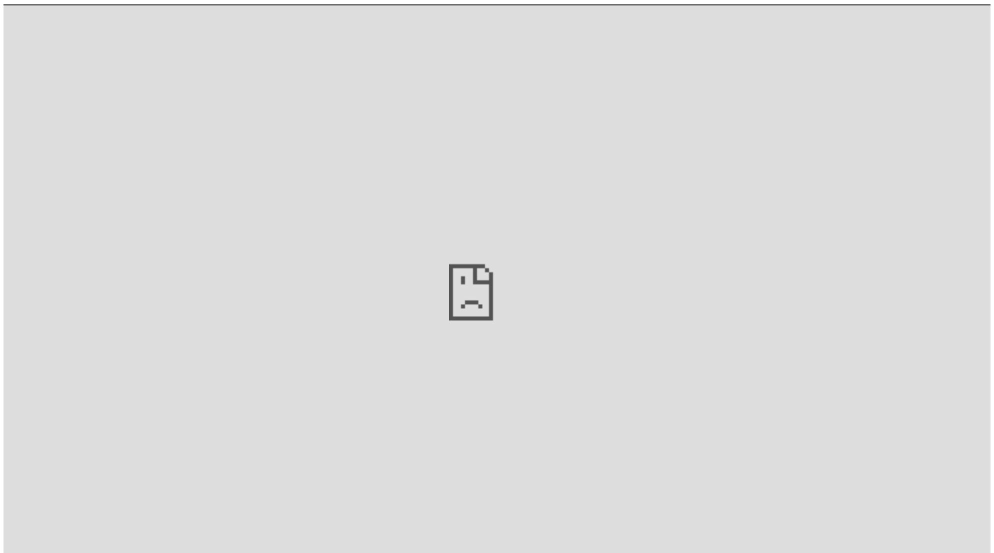
Daily Changes in Earth's Orientation to the Sun

What causes fluctuations in Sun angle and length of daylight over the course of a year? Variations occur because *Earth's orientation to the Sun continually changes*. Earth's axis (the imaginary line through the poles around which Earth rotates) is not perpendicular to the plane of its orbit around the Sun—called the *plane of the ecliptic*. Instead, the axis is tilted 23½° from the plane of the ecliptic, called the *inclination of the axis*. If the axis were not inclined, Earth would lack seasons. Because the axis is always pointed in the same direction (toward the North Star), the orientation of Earth's axis to the Sun's rays is constantly changing (Figure 2.5).

Figure 2.5 Earth–Sun relationships

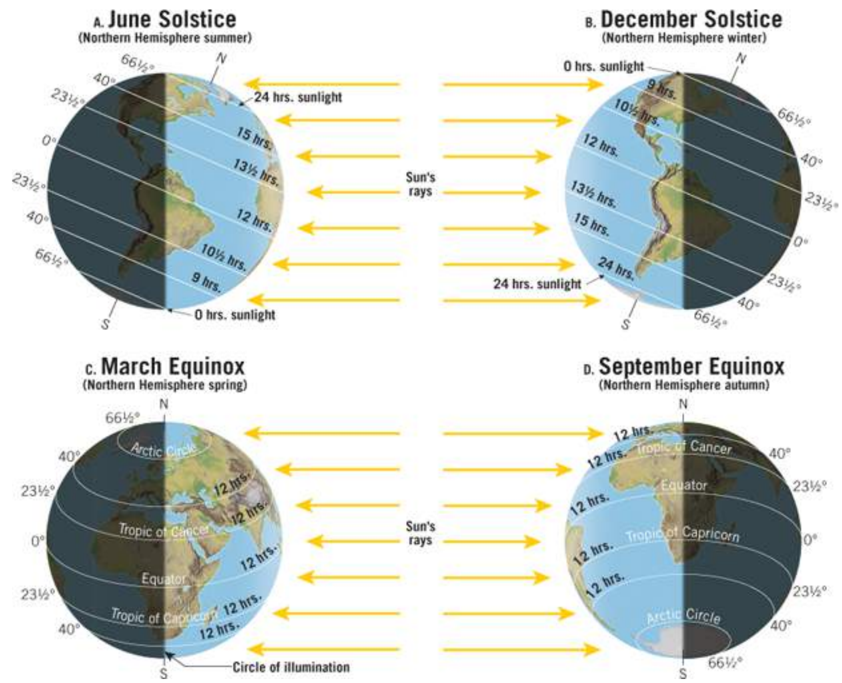


Watch **Animation: Earth-Sun Relations**

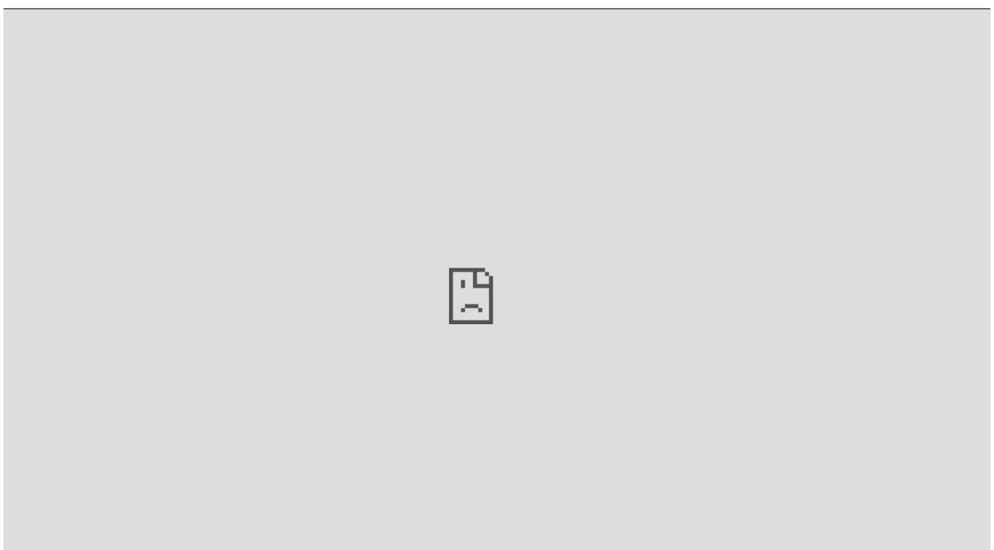


For example, on one day in June each year, Earth's position in orbit is such that the Northern Hemisphere is inclined or "leaning" 23½° *toward* the Sun (left in Figure 2.5). Six months later, in December, when Earth has moved to the opposite side of its orbit, the Northern Hemisphere "leans" 23½° *away* from the Sun (Figure 2.5, right). On days between these extremes, the "lean" of Earth's axis is less than 23½° relative to the rays of the Sun. This change in orientation causes the spot where the Sun's rays are vertical (striking the atmosphere at a 90° angle) to make an annual migration from 23½° north of the equator to 23½° south of the equator. In turn, this migration causes the angle of the noon Sun to vary 47° (23½° + 23½°) for all midlatitude locations during a year. New York City, for instance, has a maximum noon Sun angle of 73½° when the Sun's vertical rays have reached their farthest northward location in June, and a minimum noon Sun angle of 26½° 6 months later—a difference of 47° (Figure 2.6). By contrast, a city on the equator will experience an annual migration of half that amount, 23½°. Box 2.1 explains how the angle of the noon Sun can be calculated for a given latitude.

Smartfigure 2.6 **Characteristics of the solstices and equinoxes**



Watch **SmartFigure: Solstices and Equinoxes**



Box 2.1

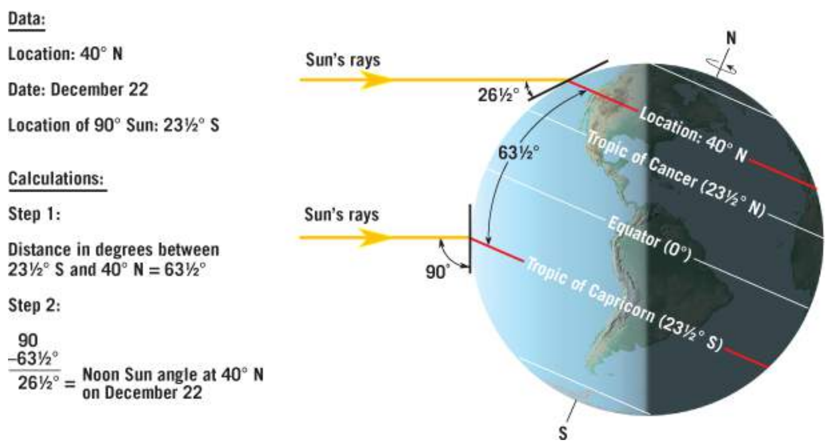
Calculating the Noon Sun Angle

Because Earth is roughly spherical, the only locations that receive vertical (90°) rays from the Sun are located along *one particular line of latitude* on any given day. As we move either north or south of this location, the Sun's rays strike at decreasing angles. Thus, the closer a place is situated to the latitude receiving the vertical rays of the Sun, the higher will be its noon Sun, and the more concentrated will be the radiation it receives.

A place located 1° away (either north or south) receives an 89° angle; a place 2° away, an 88° angle; and so forth. To calculate the noon Sun angle, simply find the number of degrees of latitude separating the location you want to know about from the latitude that is receiving the vertical rays of the Sun. Then subtract that value from 90°. The example in Figure 2.A illustrates how to calculate the noon Sun angle for a city located at 40° north latitude on December 22 (winter solstice).

Figure 2.A **Calculating the noon Sun angle**

Recall that on any given day, only one latitude receives vertical (90°) rays of the Sun. On December 22, the Sun is directly overhead at 23½° south. In this example, the number of degrees of latitude separating 40° N from the location of the Sun's vertical rays is 63½°. Subtracting this from 90° gives you a noon Sun angle of 26½°.



Apply What You Know

1. Calculate the noon Sun angle for your location on June 21 (summer solstice).

Solstices and Equinoxes

Based on Earth's position in orbit and the annual migration of the vertical rays of the Sun, 4 days each year are especially significant. On June 21 or 22, the vertical rays of the Sun strike 23½° north latitude (23½° north of the equator), a line of latitude known as the **Tropic of Cancer** (Figure 2.5). For people living in the Northern Hemisphere, June 21 or 22 is known as the **summer solstice**, the first "official" day of summer (Box 2.2).

Box 2.2

When Are the Seasons?

Have you ever been caught in a snowstorm around Thanksgiving, even though winter does not begin until December 21? Or have you endured several consecutive days of 100° temperatures although summer has not “officially” started? The idea of dividing the year into four seasons originated from the Earth–Sun relationships discussed in this chapter (Table 2.A). This astronomical definition of the seasons defines winter in the Northern Hemisphere as the period from the winter solstice (December 21–22) to the spring equinox (March 21–22). This is also the definition used most widely by the news media, yet it is not unusual for portions of the United States and Canada to have significant snowfalls weeks before the “official” start of winter.

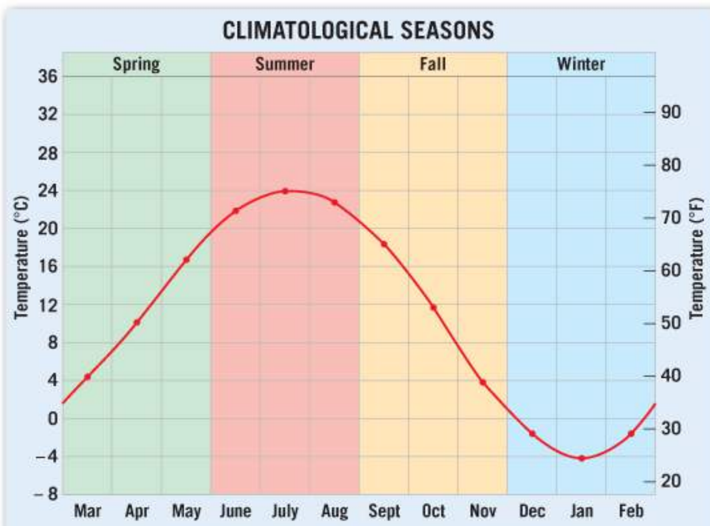
Table 2.A Occurrence of the Seasons in the Northern Hemisphere

Season	Astronomical Season	Climatological Season
Spring	March 21 or 22 to June 21 or 22	March, April, May
Summer	June 21 or 22 to September 22 or 23	June, July, August
Autumn	September 22 or 23 to December 21 or 22	September, October, November
Winter	December 21 or 22 to March 21 or 22	December, January, February

Because the weather phenomena we normally associate with each season do not coincide well with the astronomical seasons, meteorologists prefer to divide the year into four 3-month periods based primarily on temperature. Thus, winter is defined as December, January, and February, the three coldest months of the year in the Northern Hemisphere (Figure 2.B). Summer is defined as the three warmest months, June, July, and August. Spring and autumn are the transition periods between these two seasons. Inasmuch as these four 3-month periods better reflect the temperatures and weather that we associate with the respective climatological seasons, this definition of the seasons is more useful for meteorological discussions.

Figure 2.B Mean monthly temperatures for a midlatitude city in the central United States

Notice how well the three warmest and three coldest months align with the occurrence of summer and winter seasons, respectively. The astronomical seasons began about 21 days after the climatological seasons. Therefore, based on the astronomical seasons, winterlike conditions can occur long before the designated “first day of winter.”



Apply What You Know

1. Why do meteorologists most often refer to climatological seasons rather than astronomical seasons?

Six months later, on December 21 or 22, Earth tilts (or leans) in the opposite direction, so the Sun’s vertical rays strike at 23½° south latitude. (Recall that Earth’s axis always points in the same direction; it is Earth’s changing position relative to the Sun that causes the apparent change in tilt.) This line of latitude is known as the **Tropic of Capricorn**. In the

Northern Hemisphere, December 21 or 22 is the **winter solstice**, the first day of winter. However, on this same day, the Southern Hemisphere is experiencing its summer solstice.

The *equinoxes* occur midway between the solstices. September 22 or 23 is the date of the **fall (autumnal) equinox** in the Northern Hemisphere, and March 21 or 22 is the date of the **spring (vernal) equinox**. On these dates, the vertical rays of the Sun strike the equator (0° latitude) because Earth's position is such that its axis is tilted neither toward nor away from the Sun.

The length of daylight versus darkness is also determined by the position of Earth relative to the Sun's rays. The length of daylight on the summer solstice in the Northern Hemisphere, June 21, is greater than the length of night. This fact can be established by examining Figure 2.6, which illustrates the **circle of illumination**—that is, the boundary separating the dark half of Earth from the lighted half. The length of daylight is established by comparing the fraction of a line of latitude that is on the "day" side of the circle of illumination with the fraction on the "night" side. Notice that on June 21, all locations in the Northern Hemisphere experience longer periods of daylight than darkness (Table 2.1). By contrast, during the Northern Hemisphere winter solstice in December, the length of darkness exceeds the length of daylight at all locations in the hemisphere.

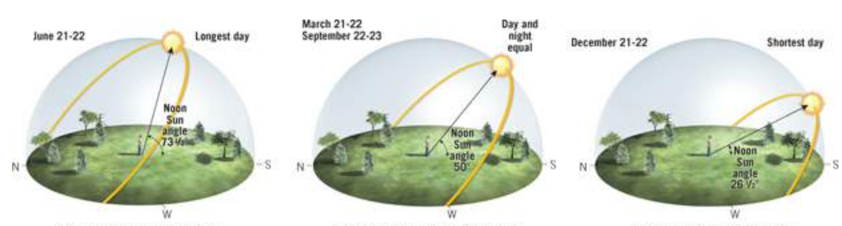
Table 2.1 Length of Daylight

Latitude	Summer Solstice	Winter Solstice	Equinoxes
0°	12 hr	12 hr	12 hr
10°	12 hr 35 min	11 hr 25 min	12 hr
20°	13 hr 12 min	10 hr 48 min	12 hr
30°	13 hr 56 min	10 hr 04 min	12 hr
40°	14 hr 52 min	9 hr 08 min	12 hr
50°	16 hr 18 min	7 hr 42 min	12 hr
60°	18 hr 27 min	5 hr 33 min	12 hr
70°	2 mo	0 hr 00 min	12 hr
80°	4 mo	0 hr 00 min	12 hr
90°	6 mo	0 hr 00 min	12 hr

The seasonal changes in length of daylight and the Sun's angle are the primary causes of the month-to-month variations in temperature observed at most locations. This is illustrated in Figure 2.7, which depicts the daily paths of the Sun over the seasons of the year for a location at 40° north latitude—New York City, for example. Notice that the length of daylight is longest during the summer solstice, whereas the opposite is true for the winter solstice. (Compare the length of the Sun's path [yellow line] for each of these days.) New York City has about 15 hours of daylight on June 21, compared to 9 hours on December 21. In addition, the maximum Sun angle is 73½°on June 21, and only 26½°on December 21.

Figure 2.7 Daily paths of the Sun

The various paths of the Sun for a place located at 40° north latitude at three different times of the year.

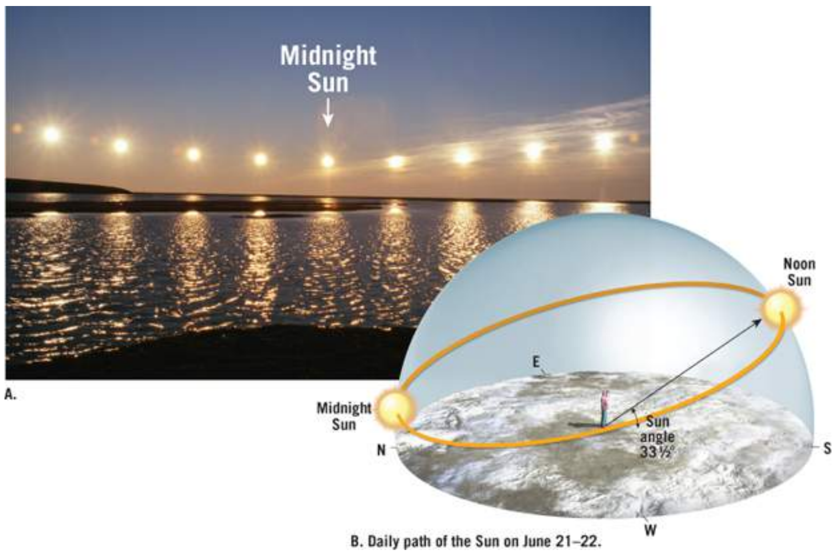


> The length of daylight is longest during the summer solstice, whereas the opposite is true for the winter solstice.

Also note from Table 2.1 that the farther north a location is from the equator on June 21, the longer the period of daylight it will experience. On this date, places located on or north of the **Arctic Circle** (66½° north latitude), experience the *midnight Sun*, a natural phenomenon in which the Sun is visible at midnight (Figure 2.8A). In fact, on this date the Sun does not set for a period that ranges from 1 day at the Arctic Circle, to about 4 months at 80° north latitude, and 6 months at the pole. Figure 2.8B shows the path of the Sun as seen by an observer located at 80° north latitude during the summer solstice. Notice that the Sun does not drop below the horizon at any time during the entire day. The **Antarctic Circle**, which is the corresponding latitude in the Southern Hemisphere, experiences the opposite situation—total darkness on June 21.

Figure 2.8 **Midnight Sun**

A. Multiple exposures (taken on the same day) of the Sun as it appears before midnight (left portion of the image) and after midnight in midsummer, at about 80° north latitude. **B.** Illustration of the path of the Sun at the same location. Notice that the Sun never sets and only gets close to the horizon at midnight.



Watch **Video: Net Radiation at the Top of the Atmosphere**

Eye on the Atmosphere 2.1

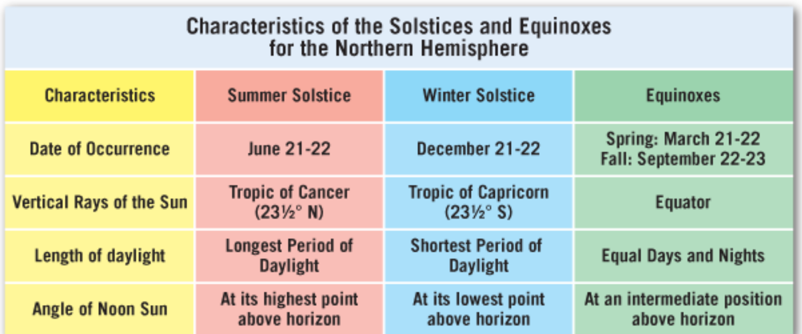
This image, which shows the *first sunrise* of 2008 at the South Pole, was taken at the U.S. Amundsen–Scott Station. At the moment the Sun cleared the horizon, the weathered American flag was seen whipping in the wind above a sign marking the location of the geographic South Pole.

Apply What You Know

1. What was the approximate date that this photograph was taken?
2. How long after this photo was taken did the Sun set at the South Pole?
3. Over the course of 1 year, what is the highest position the Sun can reach (measured in degrees) at the South Pole? On what date does this occur?

Figure 2.9 summarizes the characteristics of the solstices and equinoxes for a location in the Northern Hemisphere. When you examine Figure 2.9, you will see why a midlatitude location is warmest in the summer, when the days are longest and the angle of the Sun above the horizon is highest. Near the winter solstice, the reverse occurs: The days are shortest, and the Sun angle is lowest. During an equinox (meaning "equal night"), the length of daylight is 12 hours everywhere on Earth because the circle of illumination passes directly through the poles, thus dividing the lines of latitude in half.

Figure 2.9 Characteristics of the solstices and equinoxes for the Northern Hemisphere



Characteristics of the Solstices and Equinoxes for the Northern Hemisphere

Characteristics	Summer Solstice	Winter Solstice	Equinoxes
Date of Occurrence	June 21-22	December 21-22	Spring: March 21-22 Fall: September 22-23
Vertical Rays of the Sun	Tropic of Cancer (23½° N)	Tropic of Capricorn (23½° S)	Equator
Length of daylight	Longest Period of Daylight	Shortest Period of Daylight	Equal Days and Nights
Angle of Noon Sun	At its highest point above horizon	At its lowest point above horizon	At an intermediate position above horizon

All locations situated at the same latitude have identical Sun angles and lengths of daylight. If the Earth–Sun relationships were the only controls of temperature, we would expect these places to have identical temperatures as well. This is not the case. Other factors, such as a location's elevation or its proximity to a large body of water, also influence local temperature and will be addressed in Chapter 3.

Concept Checks 2.1

■ Briefly explain the primary causes of the seasons.

■ What is the significance of the Tropic of Cancer and the Tropic of Capricorn?

■ After examining Table 2.1, write a general statement that relates the season, latitude, and the length of daylight.

2.2 Energy, Temperature, and Heat

LO 2 Describe the different forms of energy and heat in the atmosphere: kinetic energy, potential energy, latent heat, and sensible heat.

The universe is made up of a combination of matter and energy. The concept of matter is easy to grasp because it is the “stuff” we can see, smell, and touch. Energy, by contrast, is abstract and therefore more difficult to describe and understand. Energy comes to Earth from the Sun in the form of radiation, which we see as light and feel as heat. This energy is then transformed and transported by the Earth system.

Forms of Energy

Energy can be thought of simply as having the capacity for doing work, such as making an object move. Common examples include the chemical energy from gasoline that powers automobiles, the heat energy from stoves that excites water molecules (boils water), and the gravitational energy that has the capacity to move snow down a mountain slope in the form of an avalanche. These examples illustrate that energy takes many forms and can also change from one form to another. For example, the chemical energy in gasoline is first converted to thermal energy (which we commonly refer to as heat) in the engine of an automobile, which is then converted to mechanical energy that moves the automobile along.

You are undoubtedly familiar with some of the common forms of energy, such as thermal, chemical, nuclear, radiant (light), and gravitational energy. Energy can be placed into one of two major categories: *kinetic energy* and *potential energy*.

Kinetic Energy

Energy associated with an object by virtue of its motion is described as **kinetic energy**. A simple example of kinetic energy is the motion of a hammer when driving a nail. The swinging hammer can move another object (do work). The faster the hammer is swung, the greater its kinetic energy (energy of motion). Similarly, a larger (more massive) hammer possesses more kinetic energy than a smaller one, provided that both are swung at the same velocity. Likewise, the winds associated with a hurricane possess much more kinetic energy than do light, localized breezes because hurricane winds are larger in scale (cover a larger area) and travel at higher velocities.

Kinetic energy is also significant at the atomic level. All matter is composed of atoms and molecules that are continually vibrating and, by virtue of this motion, have kinetic energy. For example, when a pan of water is heated on a stove, the water molecules begin to vibrate faster. Thus, when a solid, liquid, or gas is heated, its atoms or molecules move faster, and the material possess more kinetic energy.

Potential Energy

As the term implies, **potential energy** has the potential or capacity to do work. For example, large hailstones suspended by an updraft in a towering cloud have gravitational potential energy. If the updraft weakens, gravity will pull these hailstones to Earth to do destructive work on roofs and vehicles. Many substances, including wood, gasoline, and the food you eat, contain potential energy, which is capable of doing work, given the right circumstances.

> Energy can be categorized as either kinetic energy or potential energy.

Temperature

In everyday use, *temperature* is used to describe how warm or cold an object is, using a standard measure. In the United States, the Fahrenheit scale is used most often to express temperature. For example, the Weather Channel may forecast tomorrow's high temperature to be 88°F. However, scientists and most other countries use the Celsius and Kelvin temperature scales. A discussion of all three scales is provided in Chapter 3.

Temperature is formally defined as a *measure of the average kinetic energy of the atoms or molecules in a substance*. When a substance is heated, its molecules and atoms move faster, and its temperature rises. By contrast, when an object cools, the atoms and molecules vibrate more slowly, and its temperature drops.

It is important to note that temperature is *not* a measure of the *total* kinetic energy of an object. For example, a cup of boiling water has a much higher temperature than a bathtub of lukewarm water. However, the quantity of water in the cup is small, so it contains far less total kinetic energy than the water in the tub. Much more ice would melt in the tub of lukewarm water than in the cup of boiling water. The temperature of the water in the cup is higher because the atoms and molecules are vibrating faster, but the total amount of kinetic energy (also referred to as *heat*, or *thermal energy*) is much smaller because there are far fewer atoms and molecules.

> *Temperature* is defined as a measure of the average kinetic energy of the atoms or molecules in a substance.

Heat

Heat is defined as *energy transferred into or out of an object because of temperature differences between that object and its surroundings*. If you hold a mug of hot coffee, your hand will begin to feel warm or even hot. By contrast, when you hold an ice cube, heat is transferred from your hand to the ice cube. Heat flows from a region of higher temperature to a region of lower temperature. Once the temperatures become equal, heat flow stops.

It is also common to use the word *heat* to describe *thermal energy*, which is the energy contained in a substance as a result of its temperature. A hot object is described as containing more thermal energy or heat than a cold object of equal mass and composition. Meteorologists subdivide heat into two categories: *latent heat* and *sensible heat*.

Latent Heat

Heat is released or absorbed *when water changes from one state of matter to another*, a process called a *phase change*. For example, a phase change occurs when liquid water evaporates and becomes water vapor. During the process of evaporation, heat from the surroundings (environment) is absorbed by liquid water, causing its molecules to vibrate more rapidly. When the rate of vibration is great enough to overcome the surface tension holding together the water molecules, some of the molecules escape (evaporate) and become water vapor. Because the most energetic (fastest-moving) molecules escape, the average kinetic energy (temperature) of the remaining liquid water decreases. Therefore, *evaporation is considered a cooling process* because it removes heat from the environment. The cooling effect of evaporation is something you certainly have experienced upon stepping out, dripping wet, from a swimming pool or shower.

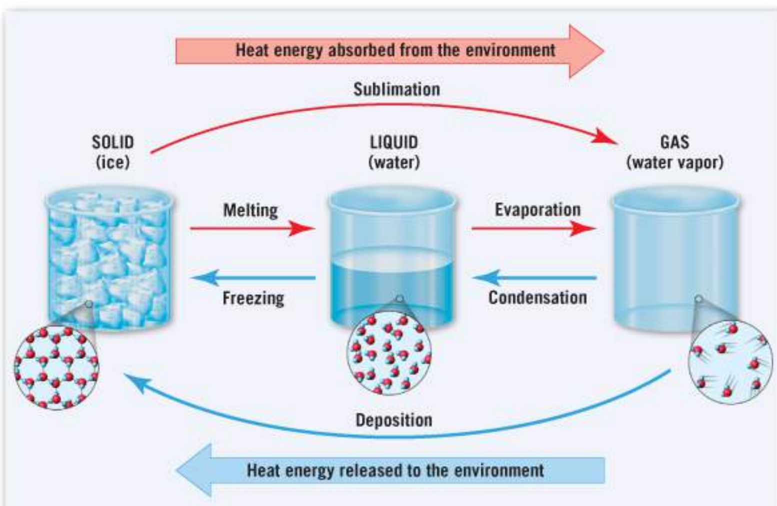
During evaporation, the energy absorbed by the escaping water vapor molecules is called **latent heat** (*latent* 5= to lie hidden). The term *latent* is used to describe this phenomenon because the thermal energy (heat) required to evaporate the water is stored, or "hidden," within the escaping water vapor. The latent heat stored in water vapor is eventually released, usually to the atmosphere, during condensation—when water vapor returns to its liquid state during cloud formation. Therefore, *condensation, the opposite of evaporation, returns energy to the environment and is considered a warming process*.

> Latent heat is the energy required to convert a solid into a liquid (or vapor), or a liquid into a vapor, without a change of temperature.

Through the combined processes of evaporation and condensation, latent heat transports large amounts of energy from Earth's surface, mainly the oceans, to the atmosphere. The importance of latent heat in atmosphere processes will be explored in Chapter 4.

Keep in mind that latent heat is exchanged between the environment and water molecules anytime water undergoes a phase change. Figure 2.10 illustrates the phase changes water undergoes; some involve the absorption and storage of latent heat, while the opposite processes release latent heat back to the environment. For example, when water vapor condenses and releases heat to the atmosphere, this is referred to as *latent heat of condensation*.

Figure 2.10 Latent heat is either absorbed or released by each of these phase changes



Sensible Heat

In contrast to latent heat, **sensible heat** is the heat that we can feel and measure with a thermometer but that does not involve a phase change. It is called *sensible* heat because it can be "sensed." On a clear summer day, the sunlight that is absorbed by the atmosphere, or by your exposed skin, will cause an increase in temperature. Like latent heat, sensible heat can be transported from one location to another. Warm air that originates over the Gulf of Mexico and flows into the Great Plains in the winter is one example.

> Sensible heat is the heat energy we feel and measure with a thermometer.

Concept Checks 2.2

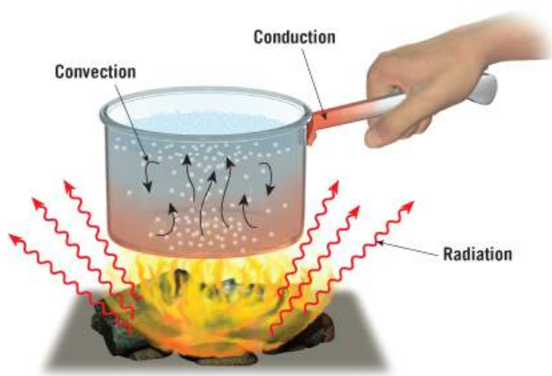
- Define *kinetic energy*, *potential energy*, and *temperature*.
- Briefly describe how latent heat is transferred from Earth's surface to the atmosphere.
- Compare latent heat and sensible heat.

2.3 Mechanisms of Heat Transfer

LO 3 List and describe the three mechanisms of heat transfer.

The flow of energy can occur in three ways: *conduction*, *convection*, and *radiation* (Figure 2.11). Although we will present them separately, all three mechanisms of heat transfer can operate simultaneously and, working in tandem, these processes can transfer heat between the Sun and Earth and between Earth's surface, its atmosphere, and outer space.

Smartfigure 2.11 Three mechanisms of heat transfer: conduction, convection, and radiation



Watch **SmartFigure: Three Mechanisms of Heat Transfer**

Conduction

Anyone who attempts to pick up a metal spoon left in a boiling pot of soup realizes that heat is transmitted along the entire length of the spoon. The transfer of heat in this manner is called *conduction*. The hot soup causes the molecules at the bowl end of the spoon to vibrate more rapidly. These molecules collide more vigorously with their neighbors and so on up the handle of the spoon. Thus, **conduction** is the transfer of heat through molecular collisions from one molecule to another. The ability of substances to conduct heat varies considerably. Metals are good *conductors*, as those of us who have touched a hot metal spoon quickly learned. Air, in contrast, is a very poor conductor of heat. Consequently, conduction is important only between Earth's surface and the air immediately in contact with the surface. Conduction is the least significant means of heat transfer for the atmosphere as a whole, and we can disregard it when considering most meteorological phenomena.

> Conduction is the molecule-to-molecule transfer of heat.

Objects that are poor conductors, such as air, are called *insulators*. Most objects that are good insulators, such as cork, plastic foam, or goose down, contain many small air spaces. The poor conductivity of the trapped air gives these materials their insulating value. Snow, like other good insulators, contains numerous air spaces that impair the flow of heat. This is why wild animals may burrow into a snowbank to escape the "cold." The snow, like a down-filled comforter, does not supply heat; it simply retards the loss of the animal's own body heat.

Convection

Much of the heat transport in Earth's atmosphere and oceans occurs by convection. **Convection** is heat transfer that involves the actual movement or circulation of a substance. It takes place in fluids (liquids such as water and gases such as air) where the material can flow.

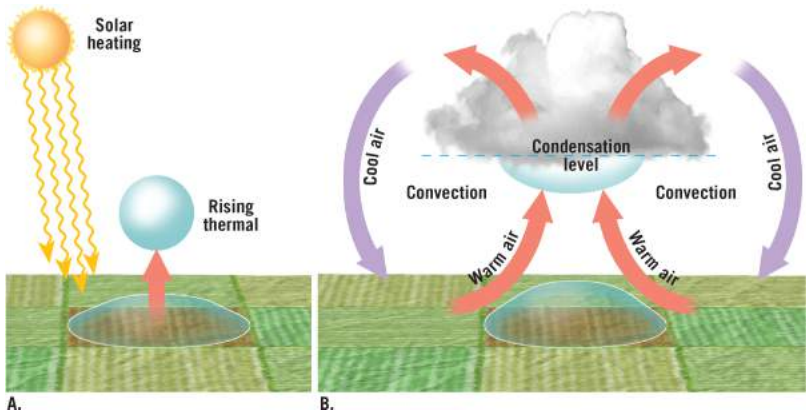
The pan of water being heated over a campfire in Figure 2.11 illustrates the nature of a simple convective circulation. The fire warms the bottom of the pan, which conducts heat to the water inside. Because water is a relatively poor conductor of heat, only the water in close proximity to the bottom of the pan is heated by conduction. Heating causes water to expand and become less dense. Thus, the hot, buoyant water near the bottom of the pan rises, while the cooler, denser water above sinks. As long as the water is heated from the bottom and cools near the top, it will continue to "turn over," producing a *convective circulation*.

> Convection is a means of heat transfer involving the movement or circulation of a substance.

In a similar manner, some of the air in the lowest layer of the atmosphere that is heated by radiation and conduction is then transported by convection to higher layers of the atmosphere. For example, on a hot, sunny day, a dark plowed field becomes warmer than the surrounding croplands, and the air above the plowed field will be heated more than the air above the crops. As warm, less-dense air above the plowed field buoys upward, it is replaced by the cooler air above the croplands (Figure 2.12). In this way, a convective flow is established. The warm parcels of rising air are called **thermals**, and they are what hang-glider pilots use to keep their crafts soaring. Convection of this type not only transfers heat but also transports moisture (water vapor) aloft. The result is an increase in cloudiness that frequently can be observed on warm summer afternoons.

Figure 2.12 Rising warmer air and descending cooler air are examples of convective circulation

A. Heating of Earth's surface produces thermals of rising air that transport heat and moisture aloft. **B.** The rising air cools, and if it reaches the condensation level, clouds form.



On a much larger scale is the global convective circulation of the atmosphere, which is driven by the unequal heating of Earth's surface. These complex movements are responsible for the redistribution of heat between hot equatorial regions and frigid polar latitudes; we will discuss them in detail in Chapter 7.

Atmospheric circulation consists of vertical as well as horizontal components, so energy is transferred both vertically and horizontally. Meteorologists often use the term *convection* to describe the part of atmospheric circulation that involves *upward and downward* motion of air. By contrast, the term **advection** is used to denote the horizontal component of airflow. A common example of advection is *wind*, a phenomenon we will examine closely in later chapters. Residents of the midlatitudes often experience the effects of heat transfer by advection. For example, when frigid Canadian air invades the U.S. Midwest in

January, it brings bitterly cold winter weather, whereas advection of latent heat from the Gulf of Mexico is a primary source of energy for spring thunderstorms.

Radiation

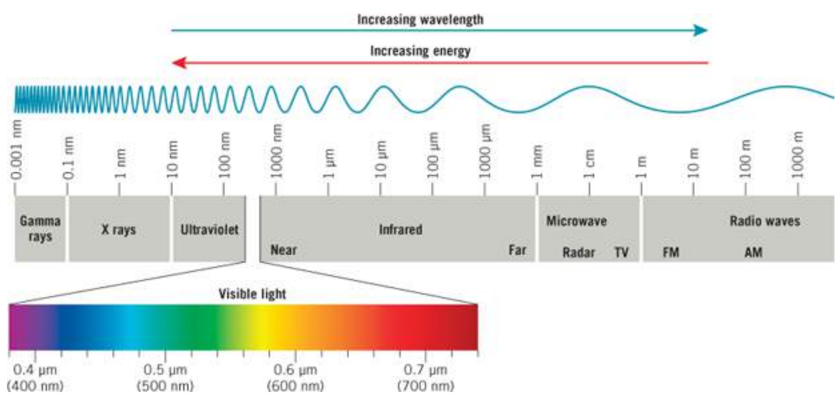
The third mechanism of heat transfer is radiation. Unlike conduction and convection, radiation is the only mechanism that can transfer thermal energy through the vacuum of space and thus is responsible for solar energy reaching Earth.

Solar Radiation

The Sun is the ultimate source of energy that drives the weather machine. We know the Sun emits light of varying energy—including visible light, infrared radiation, and ultraviolet radiation. Although these forms of energy constitute a major portion of the total energy that radiates from the Sun, they are only a part of a large array of energy called **radiation,** or **electromagnetic radiation**. This array or spectrum of electromagnetic energy is shown in Figure 2.13.

Figure 2.13 **The electromagnetic spectrum**

The names and wavelengths of various types of electromagnetic radiation are shown. A nanometer (nm) is one thousandth of a micrometer.



Watch **Video: Tour of the Electromagnetic Spectrum**

> Radiation is the only mechanism that can transfer thermal energy through the vacuum of space and is responsible for solar energy reaching Earth.

All types of radiation from the Sun travel through the vacuum of space at 300,000 kilometers (186,000 miles) per second, a value known as the *speed of light*. To help visualize radiant energy, imagine ripples made in a calm pond when a pebble is tossed in. Like the waves produced in the pond, waves of electromagnetic radiation come in various sizes, or **wavelengths**—the distance from one crest to the next (Figure 2.13). Radio waves have the longest wavelengths, up to thousands of meters in length. Gamma waves are the shortest, at less than one-billionth of a centimeter. Shortwave radiation is usually measured in **micrometers** (abbreviated μm), which are one-millionth of a meter.

> Energy from the Sun is radiated in a range of wavelengths.

Radiation is often identified by the effect that it produces when it interacts with an object. The retinas of our eyes, for instance, are sensitive to a range of wavelengths called **visible light**. We often refer to visible light as *white light* because it appears white in color. It is easy to show, however, that white light is an array of colors, each color corresponding to a specific range of wavelengths. When it is passed through a prism, white light can be divided into the colors of the rainbow, from violet (with the shortest wavelength, 0.4 micrometer [μm]) to red (with the longest wavelength, 0.7 micrometer). See Figure 2.13.

Located adjacent to the color red, and having a longer wavelength, is **infrared radiation (IR)**, which cannot be seen by the human eye but is detected as heat. On the opposite side of the visible range, located next to violet, the energy emitted is called **ultraviolet (UV) radiation** and consists of shorter wavelengths that may cause skin to become sunburned.

You might have wondered . . .

On a cold morning, why does a bathroom's tile floor feel much colder than a bedroom's carpet, even though both materials are the same temperature?

The difference you feel is due mainly to the fact that the tile is a much better conductor of heat. Hence, energy is more rapidly conducted from your bare feet to the tile floor than from your feet to the carpet. Even at room temperature (20°C [68°F]), objects that are good conductors can feel chilly to the touch. (Remember that body temperature is about 37°C [98.6°F].)

Although we divide radiant energy into categories based on our ability to perceive them, all wavelengths of radiation behave similarly. When an object absorbs any form of electromagnetic energy, the waves excite subatomic particles (electrons). This results in an increase in molecular motion and a corresponding increase in temperature. Thus, electromagnetic waves from the Sun travel through space and, upon being absorbed, increase the molecular motion of other molecules—including those that make up the atmosphere, Earth's surface, and human bodies.

One important difference among the various wavelengths of radiant energy is that *shorter wavelengths are more energetic*. This accounts for the fact that exposure to relatively short (high-energy) ultraviolet waves can cause significant sunburn, while similar exposure to longer-wavelength radiation cannot. Extended exposure to UV radiation can result in skin cancer and cataracts (see Severe & Hazardous Weather Box 2.3).

Severe & Hazardous Weather 2.3

The Ultraviolet Index

On warm days, when the sky is cloudless and bright, people enjoy spending a great deal of time outdoors "soaking up" the sunshine (Figure 2.C). For many, the goal is to develop a dark tan that sunbathers often describe as looking "healthy." Ironically, there is strong evidence that too much sunshine (specifically, too much ultraviolet radiation) can lead to premature skin aging and serious health problems such as skin cancer and cataracts.

Figure 2.C Exposure to too much ultraviolet radiation can cause serious health problems.

Since June 1994, the National Weather Service (NWS) has issued the ultraviolet (UV) index forecasts to warn the public of potential health risks of exposure to sunlight. The UV index is determined by taking into account the predicted cloud cover and reflectivity of the surface, as well as the Sun angle and atmospheric depth for each forecast location. Because atmospheric ozone strongly absorbs ultraviolet radiation, the extent of the ozone layer is also considered. The UV index values lie on a scale from 0 to 11+, with larger values representing greatest risk.

The U.S. Environmental Protection Agency (EPA) has established five exposure categories based on UV index values: Low, Moderate, High, Very High, and Extreme, as described in Table 2.B. Table 2.B also indicates the range of minutes it will take the most susceptible skin types (pale or milky white) to burn. The EPA recommends applying sunscreen with a sun-protection factor (SPF) of 30 or higher to all exposed skin (and reapplied every 2 hours). This is especially important after swimming or while sunbathing, even on cloudy days with the UV index in the Low category. The public is advised to minimize outdoor activities when the UV index is Very High or Extreme.

Table 2.B The UV Index: Minutes to Burn for the Most Susceptible Skin Type

UV Index Value	Exposure Category	Description	Minutes to Burn
0–2	Low	Low danger from the Sun's UV rays for the average person.	> 60
3–5	Moderate	Moderate risk from unprotected Sun exposure. Take precautions during midday, when sunlight is strongest.	40–60
6–7	High	Protection against sunburn is needed. Cover up, wear a hat and sunglasses, and use sunscreen.	25–40
8–10	Very High	Try to avoid the Sun between 11 A.M. and 4 P.M. Otherwise, cover up and use sunscreen.	10–25
11 +	Extreme	Take all precautions. Unprotected skin will burn in minutes. Do not pursue outdoor activities if possible.	< 10

Weather Safety

The EPA also recommends using the “shadow rule” to determine how much UV exposure you are getting:

- Your UV exposure is likely lower if your shadow is taller than you are (during early morning and late afternoon).
- Your UV exposure is likely higher if your shadow is shorter than you are (around the middle of the day).

Apply What You Know

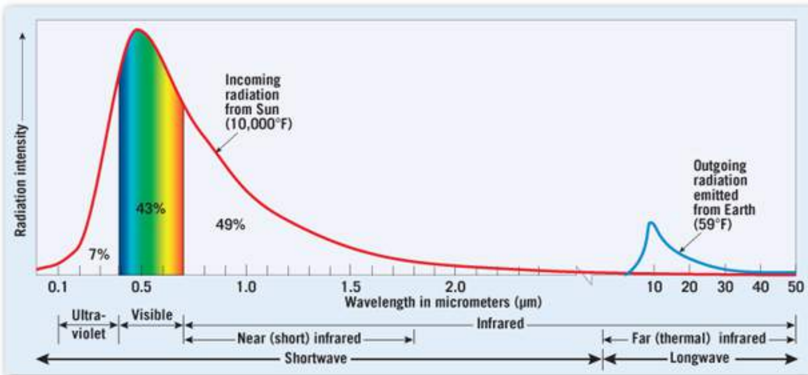
1. List several factors that are used to determine the UV index for a location.
2. Go to www.epa.gov/sunwise/uvindex.html and record your location’s UV forecast.

> Shorter wavelengths of radiation are more energetic than longer wavelengths.

It is important to note that the Sun emits all forms of radiation, but in varying quantities. Over 95 percent of all solar radiation is emitted in a narrow band between 0.1 and 2.5 micrometers, much of which is concentrated in the visible and near-infrared parts of the electromagnetic spectrum (Figure 2.14). Visible light represents over 43 percent of the total energy, infrared accounts for 49 percent, and ultraviolet, 7 percent. Less than 1 percent of solar radiation is emitted as X-rays, gamma rays, microwaves, and radio waves.

Figure 2.14 Comparison of the intensity of solar radiation and radiation emitted by Earth

Because of the Sun's high surface temperature, most of its energy is radiated at energetic wavelengths shorter than 2.5 micrometers (mm). The greatest intensity of solar radiation is in the visible range of the electromagnetic spectrum. Earth, in contrast, radiates most of its energy in wavelengths longer than 2.5 micrometers, primarily in the far end (less-energetic) of the infrared band. Thus, we call the Sun's radiation *shortwave* and Earth's radiation *longwave*.



Laws of Radiation

To better appreciate how the Sun's radiant energy interacts with Earth's atmosphere and surface, it is helpful to have a general understanding of the basic radiation laws. Although the mathematics of these laws is beyond the scope of this text, the fundamental concepts are straightforward:

1. **All objects continually emit radiant energy over a range of wavelengths.*** Not only do hot objects such as the Sun continually emit energy, but cooler objects such as Earth's polar ice caps emit energy as well.
2. **Hotter objects radiate more total energy per unit area than do colder objects.** The Sun, which has a surface temperature of 6000 K (10,000°F), emits about 160,000 times more energy per unit area than does Earth, which has an average surface temperature of 288 K (59°F).
3. **Hotter objects radiate energy in the form of shorter-wavelength radiation than do cooler objects.** We can visualize this law by imagining a piece of metal that, when heated sufficiently (as occurs in a blacksmith's shop), produces a white glow. As it cools, the metal emits more of its energy in longer wavelengths, and the glow turns a reddish color. Eventually, no light is given off, but if you place your hand near the metal, you will detect longer-wavelength infrared radiation as heat. The Sun radiates its peak energy at 0.5 micrometer, which is in the visible range (Figure 2.14). The peak radiation emitted from Earth occurs at a wavelength of 10 micrometers, well within the infrared (heat) range. Because the peak terrestrial radiation is roughly 20 times longer than the peak solar radiation, radiation emitted by Earth is often referred to as **longwave radiation**, whereas solar radiation is called **shortwave radiation**.

4. **Objects that are good absorbers of radiation are also good emitters.** Earth's surface and the Sun are nearly perfect radiators because they absorb and radiate with nearly 100 percent efficiency. Bodies that absorb and radiate all wavelengths well are called *blackbodies*. By contrast, the gases that compose our atmosphere are *selective* absorbers and emitters of radiation. For some wavelengths, the atmosphere is nearly transparent, allowing most of the energy of that wavelength to pass through. For other wavelengths, however, it is nearly opaque, absorbing most of the radiation that strikes it. Experience tells us that the atmosphere is quite transparent to visible light because these wavelengths readily reach Earth's surface.

Although the Sun is the ultimate source of radiant energy, all objects continually radiate energy over a range of wavelengths. Hot objects, such as the Sun, emit mostly shortwave (high-energy) radiation, but cooler objects, such as Earth, emit longwave (low-energy) radiation. Objects that are good absorbers of radiation, such as Earth's surface, are also good emitters. By contrast, most atmospheric gases are good absorbers (emitters) of radiation only in certain wavelengths but are poor absorbers (emitters) in other wavelengths.

Concept Checks 2.3

- Describe the three basic mechanisms of energy transfer. Which mechanism is least important meteorologically?
- Why do we describe solar radiation as shortwave radiation and radiation coming from Earth as longwave radiation?
- Describe the relationship between the temperature of a radiating body and the wavelengths it emits.

* The temperature of the object must be above a theoretical value called *absolute zero* (−273°C or 0°K) in order to emit radiant energy. For more explanation, see the subsection “Temperature Scales” in Chapter **3**.

2.4 What Happens to Incoming Solar Radiation?

LO 4 Describe what happens to incoming solar radiation.

When solar radiation enters Earth's atmosphere, three different things may occur simultaneously. First, air, which is transparent to certain wavelengths of radiation, may simply *transmit* energy—allowing it to pass through without redirecting or absorbing it. Second, some of the energy may be *absorbed*. Recall that when radiant energy is absorbed, the molecules begin to vibrate faster, which causes an increase in temperature. Third, some radiation may "bounce off" gas molecules or dust particles in the atmosphere, without being absorbed or transmitted.

> Solar radiation may be transmitted, absorbed, or reflected and scattered once it reaches the atmosphere.

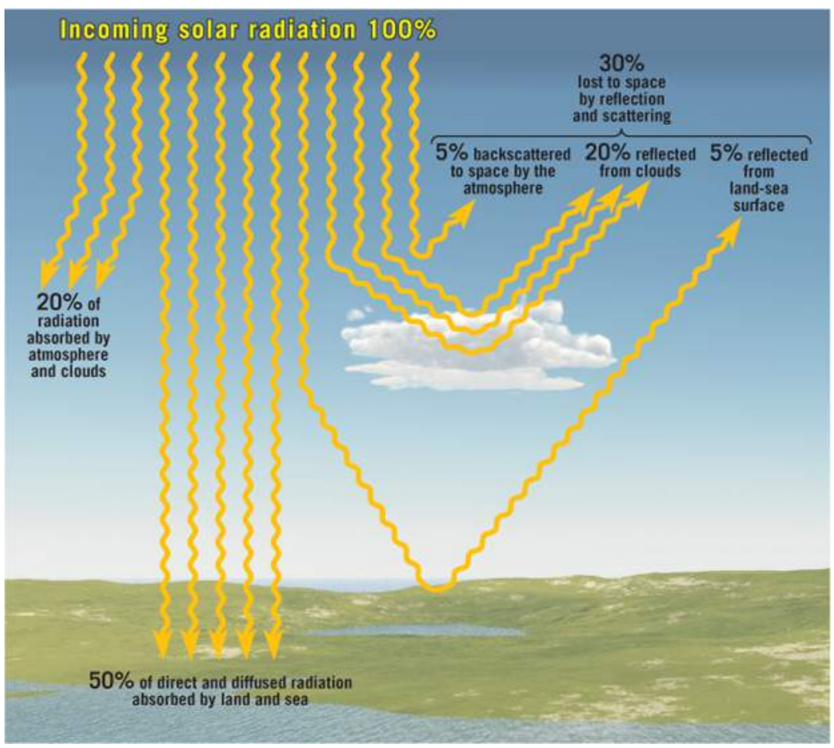
What determines whether solar radiation will be transmitted to the Earth's surface, absorbed by the gases and particles in the atmosphere, or scattered or reflected by these gases and particles? As you will see, it depends greatly upon the *wavelength* of the radiation, as well as the *size and nature of the intervening material*.

Transmission

Transmission is the process by which energy passes though the atmosphere (or any transparent media) without interacting with the gases or other particles in the atmosphere. About half of the incoming shortwave (solar) energy that reaches Earth's surface is transmitted through the atmosphere. The remainder is redirected by gas molecules and particles in the atmosphere and arrives as diffused light. Figure 2.15 illustrates what happens to incoming solar radiation, averaged for the entire globe. Notice that on average, about 55 percent of incoming solar energy reaches Earth's surface—about 50 percent is absorbed at the surface, and the remaining 5 percent is reflected back toward space.

Smartfigure 2.15 Average distribution of incoming solar radiation

More solar energy is absorbed by Earth's surface than by the atmosphere.



Watch **SmartFigure: Solar Radiation Paths**

Absorption

The amount of energy absorbed by an object depends on the wavelength of the radiation and the object's **absorptivity**. In the visible range, the degree of absorptivity is largely responsible for the brightness of an object. Surfaces that are good absorbers of all wavelengths of visible light appear black in color, whereas light-colored surfaces have a much lower absorptivity. That is why wearing light-colored clothing on a sunny summer day may help keep you cooler.

Although Earth's surface is a relatively good absorber (effectively absorbing most wavelengths of solar radiation), the atmosphere is not. As a result, gases in the atmosphere absorb only 20 percent of the solar radiation that reaches Earth (Figure 2.15). The atmosphere is a less effective absorber because gases are selective absorbers (and emitters) of radiation.

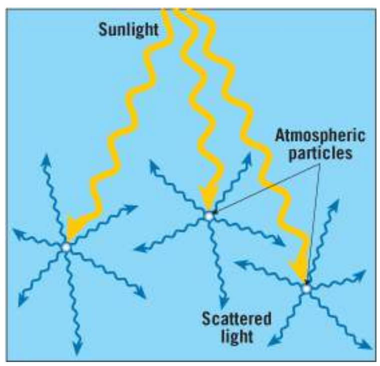
Freshly fallen snow is another example of a selective absorber. Snow is a poor absorber of visible light (reflecting up to 90 percent) and therefore the temperature directly above a snow-covered surface is colder than it would otherwise be because the snow reflected away much of the incoming radiation. By contrast, snow is a very good absorber (absorbing up to 95 percent) of longwave (infrared) radiation that is emitted from Earth's surface. As the ground radiates heat upward, the lowest layer of snow absorbs this energy and radiates some of the energy back downward. Thus, a winter's frost cannot penetrate very deeply into snow-covered ground compared to an equally cold region without snow—giving credence to the statement "The ground is blanketed with snow." Farmers who plant winter wheat desire a deep snow cover because it insulates their crops from bitter winter temperatures.

Reflection and Scattering

Reflection is the process whereby light bounces back from an object at about the same angle and intensity at which it was received. By contrast, **scattering** is a general process in which radiation bounces off an obstacle in many directions. Atoms, molecules, or tiny particles in the atmosphere cause incoming sunlight to scatter (Figure 2.16). Whether solar radiation is reflected or scattered depends largely on the size of the intervening particles and the wavelength of the light.

Figure 2.16 Scattering by atmospheric particles

When sunlight is scattered, the rays travel in different directions. Usually more energy is scattered in the forward direction than is backscattered.

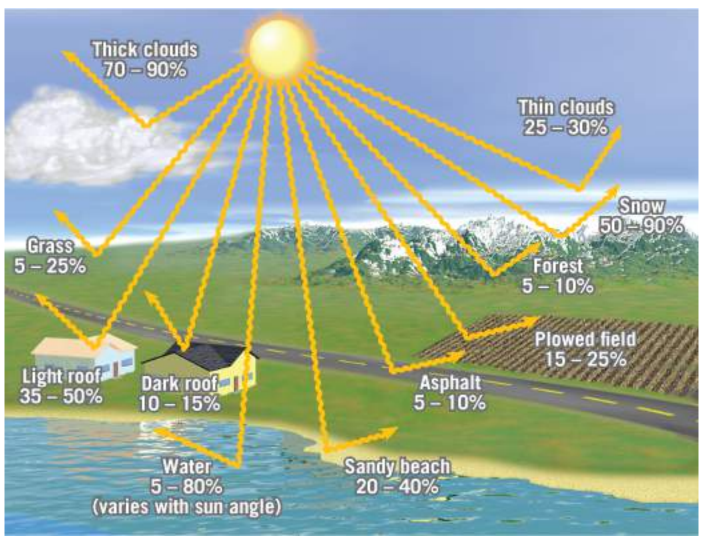


Reflection and Earth's Albedo

The fraction of radiation that is reflected by an object is called its **albedo**. Figure 2.17 gives the albedos for various surfaces. Fresh snow and thick clouds have high albedos (that is, they are good reflectors). You can observe the high reflectivity of clouds when you look down on bright clouds during an airline flight. By contrast, dark soils and parking lots have low albedos and thus absorb much of the radiation they receive. In the case of a lake or the ocean, the angle at which the Sun's rays strike the water surface greatly affects its albedo.

Figure 2.17 Albedo (reflectivity) of various surfaces

In general, light-colored surfaces tend to be more reflective than dark-colored surfaces and thus have higher albedos.



Earth's total albedo, called *planetary albedo*, is 30 percent (see Figure 2.15). This energy is lost to Earth and does not play a role in heating the atmosphere or Earth's surface. The amount of light reflected from Earth's surface represents a small percentage of the total planetary albedo. Not surprisingly, thick clouds, which have high albedos, are largely responsible for most of Earth's "brightness" as seen from space.

Scattering and Diffused Light

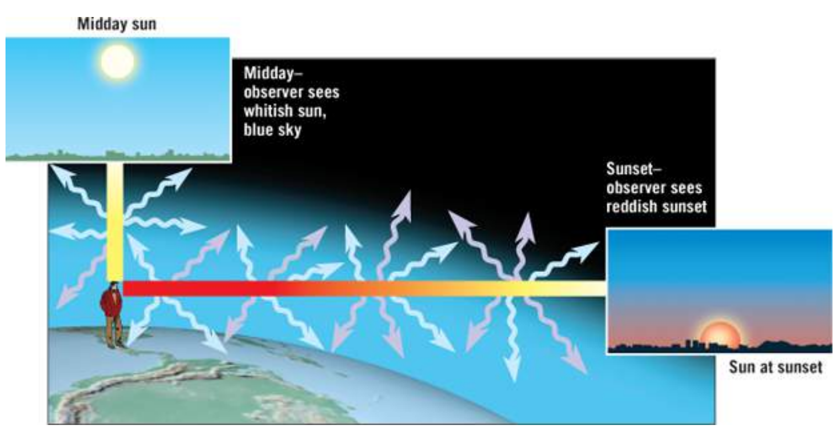
Although incoming solar radiation travels in a straight line, small dust particles and gas molecules in the atmosphere scatter some of this energy in different directions. The result, called **diffused light**, explains how light reaches the area under the limbs of a tree and how a room is lit in the absence of direct sunlight. In contrast, bodies without atmospheres, such as the Moon and Mercury, have dark skies and “pitch-black” shadows, even during daylight hours. Overall, about one-half of the solar radiation that is absorbed at Earth’s surface arrives as diffused (scattered) light.

Blue Skies and Red Sunsets

The two factors that produce Earth's blue skies and red sunsets are the selective scattering of solar radiation by atmospheric gases and the amount of atmosphere through which the Sun's rays travel before reaching Earth. Recall that sunlight appears white but is composed of all the colors of the rainbow. Atmospheric gases scatter shorter-wavelength (blue/violet) light more effectively than they scatter longer-wavelength (red/orange) light. Because shortwave radiation is selectively scattered, when you look in any direction away from the direct Sun, you observe the short-wavelength (blue) light (Figure 2.18). Scattering of visible light by atmospheric gases is called *Rayleigh scattering*.

Figure 2.18 Selective scattering by gas molecules in Earth's atmosphere produces blue skies and red sunsets

Short wavelengths (blue and violet) of visible light are scattered more effectively than are longer wavelengths (red and orange). Therefore, when the Sun is overhead, an observer can look in any direction and see predominantly blue light that was selectively scattered by the gases in the atmosphere. By contrast, at sunset, the path that light must take through the atmosphere is much longer. Consequently, most of the blue light is scattered away before it reaches an observer. Thus, the Sun appears reddish in color.



The Sun appears reddish when viewed near Earth's horizon at sunrise or sunset because solar radiation must travel a greater distance through the atmosphere before it reaches your eyes. During its travel, shorter-wavelength blue and violet wavelengths are preferentially scattered away, so the light that reaches your eyes consists mostly of red and orange hues. In other words, the sky and clouds are illuminated by light from which the blue color has been preferentially scattered away.

On Earth, the most spectacular sunsets occur when large quantities of tiny dust or smoke particles penetrate the stratosphere. (Scattering of visible light by dust or smoke is called *Mei scattering*.) For 3 years after the great eruption of the Indonesian volcano Krakatau in 1883, brilliant sunsets occurred worldwide. In addition, the European summer that followed this colossal explosion was cooler than normal, which has been attributed to the loss of incoming solar radiation due to an increase in backscattering.

Crepuscular Rays and White Clouds

Large particles associated with haze, fog, and cloud droplets scatter light more equally at all wavelengths. Because no color predominates over any other, the sky appears white or gray on days when large particles are abundant. Scattering of sunlight by haze, water droplets, or dust particles makes it possible for us to observe bands (or rays) of sunlight called *crepuscular rays*. These bright fan-shaped bands are most commonly seen when the Sun shines through a break in the clouds, as shown in Figure 2.19.

Figure 2.19 Crepuscular rays produced when haze scatters light

Crepuscular rays are most commonly seen when the Sun shines through a break in the clouds.

> The color of the sky is an indication of the size of particles present—small particles produce red sunsets, whereas large particles produce white or gray skies.

The color of the sky gives an indication of the size of particles present. Numerous small particles produce red sunsets, whereas large particles produce white (gray) skies. Thus, the bluer the sky, the less polluted the air.

Concept Checks 2.4

- Prepare and label a simple sketch that shows what happens to incoming solar radiation.
- Why does the daytime sky usually appear blue if the sky is clear?
- Why might the sky have a red or orange hue near sunrise or sunset?

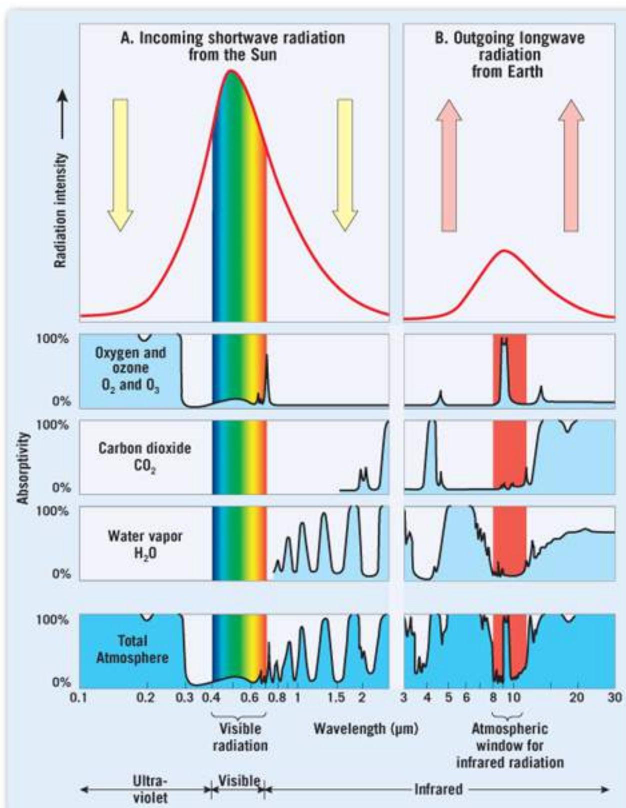
2.5 The Role of Gases in the Atmosphere

LO 5 Explain how the greenhouse effect works and why it is important.

Understanding how the atmosphere is heated requires an understanding of how atmospheric gases interact with the short-wavelength *incoming* solar radiation and the long-wavelength *outgoing* radiation emitted by Earth. Figure 2.20 shows that the majority of solar radiation is emitted in wavelengths shorter than 2.5 micrometers—shortwave radiation. By contrast, most radiation from Earth's surface is emitted at wavelengths between 2.5 and 30 micrometers—longwave radiation.

Figure 2.20 Absorption of solar and terrestrial radiation by gases in the atmosphere

The graph depicts the effectiveness of selected gases of the atmosphere in absorbing incoming shortwave radiation (left side) and outgoing longwave terrestrial radiation (right side). The blue areas represent the percentage of radiation absorbed by the various gases. The atmosphere as a whole is quite transparent to visible radiation, so most visible light reaches the ground. Some longwave (infrared) radiation escapes to space through the atmospheric window, but most is absorbed by the atmosphere.



Heating the Atmosphere

When a gas molecule absorbs radiation, the energy is transformed into kinetic energy, which is detectable as a rise in temperature (sensible heat). For example, the absorption of UV energy by oxygen molecules in the stratosphere accounts for the high temperatures experienced there.

The lower part of Figure 2.20 gives the absorptivity of the principal atmospheric gases. The only significant absorbers of incoming solar radiation are water vapor, oxygen, and ozone, which account for most of the solar energy absorbed directly by the atmosphere. Oxygen removes most of the shorter-wavelength UV radiation high in the atmosphere, and ozone absorbs UV rays in the stratosphere between 10 and 50 kilometers (6 and 30 miles). If most UV radiation were not absorbed before it reaches Earth's surface, human life would not be possible because UV energy disrupts our genetic code.

> The atmosphere is nearly transparent to incoming shortwave radiation, but relatively opaque to outgoing longwave radiation.

At the bottom of Figure 2.20, you can see that for the atmosphere as a whole, none of the gases are effective absorbers of visible radiation with wavelengths between 0.3 and 0.7 micrometer. This visible light band constitutes about 43 percent of the energy radiated by the Sun. Because the atmosphere is a poor absorber of visible radiation, most of this energy is transmitted to Earth's surface. Thus, we say that *the atmosphere is nearly transparent to incoming solar radiation. Solar energy is not an effective "heater" of Earth's atmosphere*.

The atmosphere is generally a relatively efficient absorber of longwave (infrared) radiation emitted by Earth (see the bottom right of Figure

2.20). Water vapor and carbon dioxide are the principal absorbing gases, with water vapor absorbing about 60 percent of this terrestrial radiation. Therefore, water vapor, more than any other gas, accounts for the warm temperatures of the lower troposphere, where it is most highly concentrated.

Although the atmosphere is an effective absorber of most radiation emitted by Earth's surface, it is quite transparent to the band of radiation between 8 and 12 micrometers. Notice in Figure 2.20 (lower right) that the gases in the atmosphere (mainly CO_2, and H_2O) absorb minimal energy in these wavelengths. Because the atmosphere is transparent to radiation between 8 and 12 micrometers, much as window glass is transparent to visible light, this band is called the **atmospheric window**. Although other "atmospheric windows" exist, the one located between 8 and 12 micrometers is the most significant because it is located where Earth's radiation is most intense. Thus, the atmospheric window is important because it allows longwave radiation from Earth's surface to pass directly to space without being absorbed. In addition, the atmospheric window allows satellites to detect outgoing longwave radiation and monitor what's happening at the surface and in the atmosphere.

By contrast, clouds that are composed of tiny liquid droplets (not water vapor) are excellent absorbers of the energy in the atmospheric window. Clouds absorb outgoing longwave radiation and radiate much of this energy back to Earth's surface. Thus, clouds serve a purpose similar to window blinds because they effectively block the atmospheric window and lower the rate at which Earth's surface cools. This explains why nighttime temperatures remain higher on cloudy nights than on clear nights.

Because the atmosphere is largely transparent to solar (shortwave) radiation but more absorptive of terrestrial (longwave) radiation, the atmosphere is heated from the ground up. This explains the general drop in temperature with increased altitude in the troposphere. The farther from the "radiator" (Earth's surface), the colder it gets. On average, the temperature drops 6.5°C for each kilometer (3.5°F per 1000 feet) increase in altitude, a figure known as the *normal lapse rate* (see Chapter 1). The fact that the atmosphere does not acquire the bulk of its energy directly from the Sun but is heated by Earth's surface is of utmost importance to the dynamics of the weather.

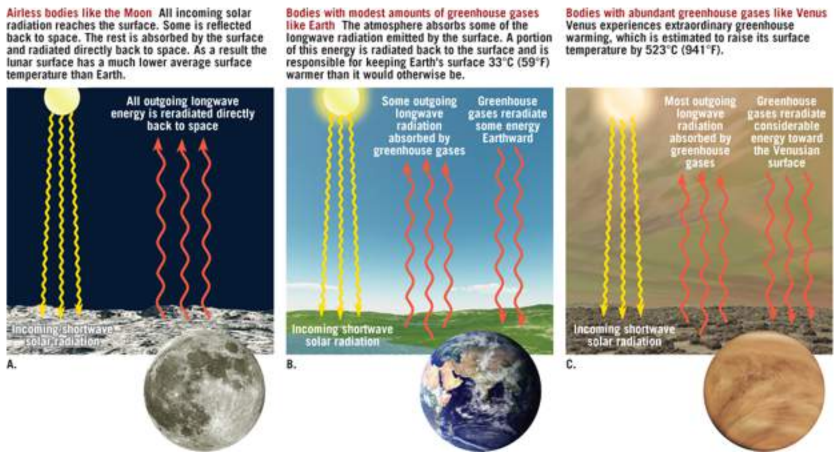
The Greenhouse Effect

Research of “airless” planetary bodies such as the Moon have led scientists to determine that if Earth had no atmosphere, it would have an average surface temperature below freezing. Fortunately, Earth’s atmosphere “recycles” some of the outgoing radiation, which makes our planet habitable.

As discussed earlier, clear skies are largely transparent to incoming shortwave solar radiation and transmit much of the shortwave radiation to Earth’s surface. This radiation is absorbed at the surface and eventually reradiated skyward as longwave terrestrial radiation. Gases that absorb longwave radiation are called **greenhouse gases**. Two atmospheric gases, *water vapor* and *carbon dioxide*, absorb a significant portion of the longwave radiation emitted by Earth’s surface. As Earth’s radiation heats these absorptive gases, the temperature of the atmosphere increases. The atmosphere, in turn, radiates some of this energy *out to space*, but more important, it radiates an equivalent amount *back toward Earth’s surface*, where it further warms the lower atmosphere. This process is known as the **greenhouse effect**. Without this complicated game of “pass the hot potato,” Earth’s average temperature would be –18°C (0°F) rather than the current temperature of 15°C (59°F) (Figure 2.21).

Smartfigure 2.21 **The greenhouse effect**

A. Airless bodies such as the Moon experience no greenhouse effect. **B.** On bodies with modest amounts of greenhouse gases, such as Earth, the greenhouse effect is responsible for keeping Earth’s surface 33°C (59°F) warmer than it would be otherwise. **C.** Bodies with abundant greenhouse gases, such as Venus, experience extraordinary greenhouse warming, which is estimated to raise its surface temperature by 523°C (941°F).



Watch **SmartFigure: 3 Planets, 3 Climates**

When you think of the greenhouse effect, you probably think of the greenhouses that are used for growing plants. The glass in a greenhouse allows shortwave solar radiation to enter and be absorbed by the objects inside. These objects, in turn, radiate energy, but at longer wavelengths that warm the air inside the greenhouse. Unlike the atmosphere, the glass ceiling prevents convection and traps the heat inside the greenhouse. Despite this difference, the term *greenhouse effect* is still used to describe atmospheric heating.

> The greenhouse effect is a natural phenomenon that warms the surface and lower atmosphere, making Earth habitable.

Media reports frequently and erroneously identify the greenhouse effect as the “villain” in the global warming problem. However, the greenhouse effect and global warming *are different concepts*. Without the greenhouse effect, Earth would be uninhabitable. Scientists have mounting evidence that human activities (particularly the release of carbon dioxide into the atmosphere) are responsible for a rise in global temperatures (see Chapter 14). Thus, humans are compounding the effects of an otherwise natural process (the greenhouse effect). It is incorrect to equate the greenhouse phenomenon, which makes life possible, with global warming—which involves undesirable changes to our atmosphere and is caused mainly by human activities.

Concept Checks 2.5

- Explain why the atmosphere is heated chiefly by radiation from Earth’s surface rather than by direct solar radiation.
- Which gases are the primary absorbers of longwave radiation in the lower atmosphere?
- Describe the process called the greenhouse effect. How is a greenhouse different from the greenhouse effect?

2.6 Earth's Energy Budget

LO 6 Describe the major components of Earth's annual energy budget.

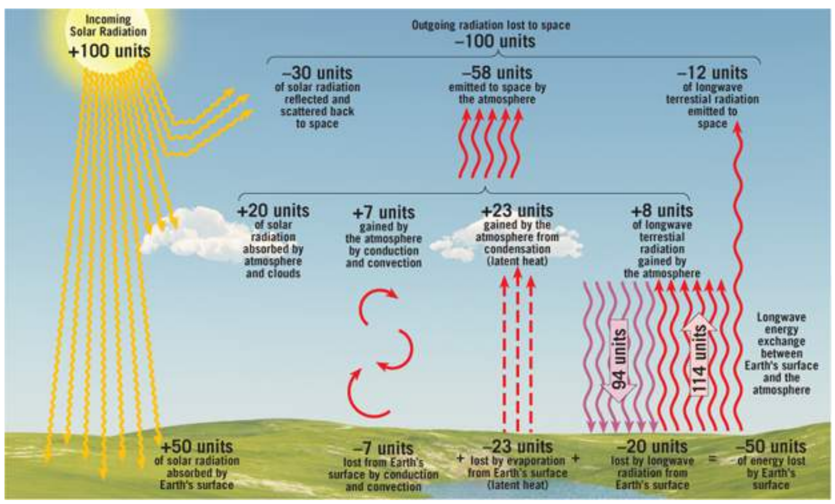
Globally, Earth's average temperature remains relatively constant, despite seasonal cold spells and heat waves. This stability indicates that a balance exists between the amount of incoming solar radiation and the amount of radiation emitted back to space; otherwise, Earth would be getting progressively colder or warmer. In addition, the energy exchanged between the Earth's surface and the atmosphere must also remain stable. This surface-to-atmosphere equilibrium is accomplished through conduction, convection, and the transfer of latent heat as well as by the transmission of longwave radiation between the Earth's surface and the atmosphere. The annual balance of incoming and outgoing radiation, as well as the energy balance that exists between Earth's surface and its atmosphere, is generally referred to as Earth's **annual energy budget**. Further discussion of Earth's changing climate can be found in Chapter 14.

Annual Energy Budget

Figure 2.22 illustrates Earth's annual energy budget. For simplicity, we will use 100 units to represent the solar radiation intercepted at the outer edge of the atmosphere. You have already seen in Figure 2.15 that, of the total radiation that reaches Earth, roughly 30 units (30 percent) are reflected and scattered back to space. The remaining 70 units are absorbed: 20 units within the atmosphere and 50 units by Earth's surface. How does Earth transfer this energy back to space?

Figure 2.22 Earth's energy budget

These estimates of the average global energy budget come from satellite observations and radiation studies. As more data are accumulated, these numbers will be modified.



If all the energy absorbed by our planet were radiated directly and immediately back to space, Earth's heat budget would be simple: 100 units of radiation received and 100 units returned to space. In fact, this does happen *over time* (minus small quantities of energy that become locked up in biomass that may eventually become fossil fuel). What complicates the heat budget is the behavior of certain greenhouse gases, particularly water vapor and carbon dioxide. As you have learned, these greenhouse gases absorb a large share of outward-directed infrared radiation and radiate much of that energy back to Earth. This “recycled” energy significantly increases the radiation received by Earth’s surface. In addition to the 50 units received directly from the Sun, Earth’s surface receives longwave radiation emitted downward by the atmosphere (94 units).

A balance is maintained because all the energy absorbed by Earth’s surface is returned to the atmosphere and eventually radiated back to space. Earth’s surface loses energy through a variety of processes: the emission of longwave radiation; conduction and convection; and energy loss to Earth’s surface through the process of evaporation—latent heat (Figure 2.22). Most of the longwave radiation emitted skyward is reabsorbed by the atmosphere. Conduction results in the transfer of energy between Earth’s surface to the air directly above, while convection carries the warm air located near the surface upward as thermals (7 units).

Earth’s surface also loses a substantial amount of energy (23 units) through evaporation. This occurs because energy is required for liquid water molecules to leave the surface of a body of water and change to its gaseous form, water vapor. The energy lost by a water body is carried into the atmosphere by molecules of water vapor. Recall that the heat used to evaporate water is referred to as *latent heat* (hidden heat). If the water vapor condenses to form cloud droplets, the energy released by condensation will be detectable as *sensible heat* (heat we can feel and measure with a thermometer). Through the process of evaporation, water molecules in gas form carry latent heat into the atmosphere, where it is eventually released.

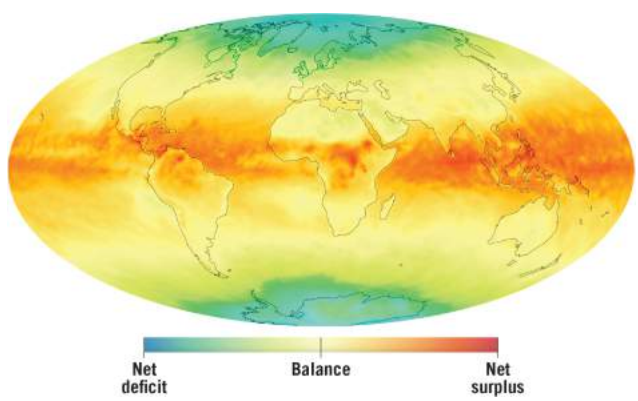
> The quantity of incoming solar radiation is, over time, balanced by the quantity of longwave radiation that is radiated back to space.

Latitudinal Energy Budget

Because incoming solar radiation is roughly equal to the amount of outgoing radiation, on average, worldwide temperatures remain nearly constant. However, although there is a balance of incoming and outgoing radiation over the entire planet, it is not maintained at each latitude (Figure 2.23). A rather wide zone that spans the equator *receives more solar radiation than is lost to space*. The opposite is true for higher latitudes, where *more heat is lost through radiation emitted by Earth than is received from the Sun*.

Figure 2.23 Radiation map showing the imbalance of incoming solar radiation and outgoing terrestrial radiation for a typical year

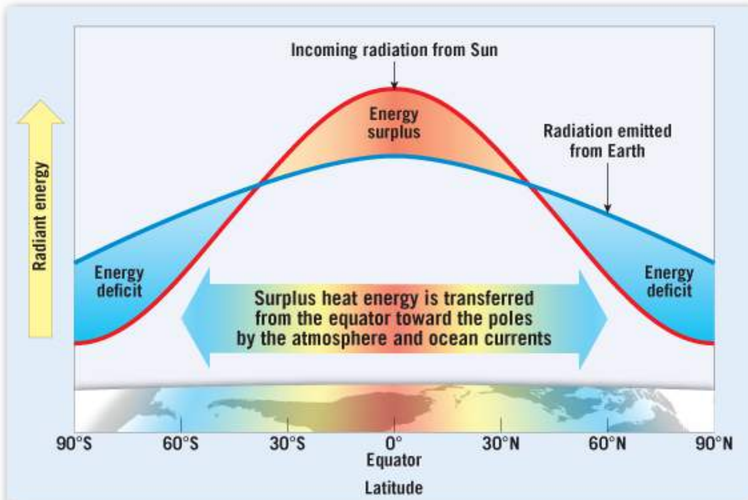
Areas near the equator receive more solar radiation than they radiate back to space and hence have a net surplus of radiation (shown in orange and red). The opposite situation occurs for polar regions.



We might conclude that the tropics are getting hotter and the poles are getting colder. But that is not the case. Instead, the global wind systems and, to a lesser extent, the oceans act as giant thermal engines, transferring surplus heat from the tropics poleward (Figure 2.24). In effect, the energy imbalance drives the winds and the ocean currents. Stated another way, the transfer of surplus heat between the tropics and the poles drives Earth's weather system.

Figure 2.24 **Latitudinal heat balance, averaged over an entire year**

The global wind system and, to a lesser extent, the oceans act as giant thermal engines, transferring surplus heat from the tropics poleward.



> The transfer of surplus heat between the tropics and the poles drives Earth's weather system.

Most heat transfer across North America occurs in the middle latitudes—from New Orleans at 30° north latitude, to Winnipeg, Manitoba, at 50° north latitude. Consequently, this is also the zone where the majority of stormy weather occurs. These processes are discussed in more detail in later chapters.

Concept Checks 2.6

■ The tropics receive more solar radiation than is lost. Why then don’t the tropics keep getting hotter?

■ What two phenomena result from the imbalance of heating that exists between the tropics and the poles?

Concepts in Review

2.1 Earth–Sun Relationships

LO 1 Explain what causes the Sun angle and length of daylight to change throughout the year. Describe how these changes result in seasonal changes in temperature.

Key Terms

rotation

orbit

perihelion

aphelion

Tropic of Cancer

summer solstice

Tropic of Capricorn

winter solstice

fall (autumnal) equinox

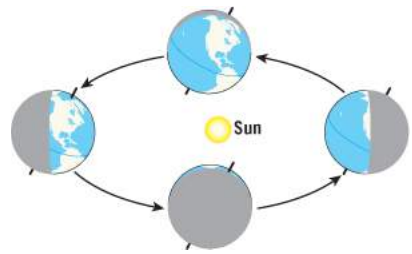
spring (vernal) equinox

circle of illumination

Arctic Circle

Antarctic Circle

- The seasons are caused by changes in the angle at which the Sun's rays strike Earth's surface and the changes in the length of daylight at each latitude. These seasonal changes result from the tilt of Earth's axis as it revolves around the Sun.
- When the Sun is directly overhead (at a 90° angle to Earth's surface), the solar rays are most concentrated and thus most intense. At lower Sun angles, the rays become more spread out and less intense.


Sun

2.2 Energy, Temperature, and Heat

LO 2 Describe the different forms of energy and heat in the atmosphere: kinetic energy, potential energy, latent heat, and sensible heat.

Key Terms

energy

kinetic energy

potential energy

temperature

heat

latent heat

sensible heat

- Energy is the ability to do work. The two major categories of energy are (1) kinetic energy, which can be thought of as energy of motion; and (2) potential energy, energy that has the capability to do work.
- Temperature is a measure of the average kinetic energy of the atoms or molecules in a substance.
- Heat is the transfer of energy into or out of an object due to temperature differences between that object and its surroundings. Heat flows from regions of higher temperature to regions of lower temperature.
- Latent heat is the energy involved when water changes from one state of matter to another. During evaporation, energy is stored as latent, or "hidden," heat within the escaping water vapor molecules. This same heat is eventually released when water vapor condenses to form water droplets in clouds.
- Sensible heat is the heat we can feel and measure with a thermometer, and it does not involve a phase change. It is called sensible heat because it can be "sensed" as a change in temperature.

2.3 Mechanisms of Heat Transfer

LO 3 List and describe the three mechanisms of heat transfer.

Key Terms

conduction

convection

thermal

advection

radiation (electromagnetic radiation)

wavelength

micrometer

visible light

infrared radiation (IR)

ultraviolet (UV) radiation

longwave radiation

shortwave radiation

- Conduction is the transfer of heat through matter by collisions between molecules and atoms. Because air is a poor conductor, conduction is significant only between Earth's surface and the air in immediate contact with the surface.
- Convection is heat transfer that involves the actual movement or circulation of a substance. Convection is an important mechanism of heat transfer in the atmosphere, where warm air rises and cooler air descends.
- Radiation (electromagnetic radiation) is the only mechanism to transfer heat through the vacuum of space. It consists of a large array of light energy that includes X-rays, visible light, heat waves, microwaves, and radio waves. Shorter wavelengths of radiation have greater energy.

- These are four basic laws of radiation: (1) All objects emit radiant energy; (2) hotter objects radiate more total energy per unit area than colder objects; (3) the hotter the radiating body, the shorter the wavelength of maximum radiation; and (4) objects that are good absorbers of radiation are also good emitters.

2.4 What Happens to Incoming Solar Radiation?

LO 4 Describe what happens to incoming solar radiation.

Key Terms

transmission

absorptivity

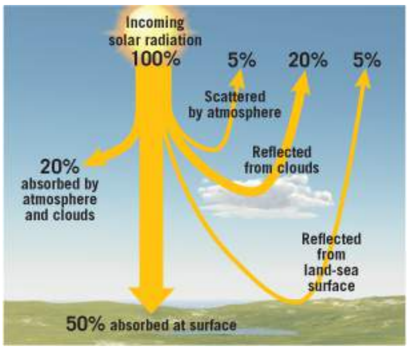
reflection

scattering

albedo

diffused light

- Approximately 50 percent of the solar radiation that strikes the atmosphere reaches Earth's surface. About 30 percent is reflected back to space. Clouds and the atmosphere's gases absorb the remaining 20 percent of the incoming solar energy.



2.5 The Role of Gases in the Atmosphere

LO 5 Explain how the greenhouse effect works and why it is important.

Key Terms

atmospheric window

greenhouse gases

greenhouse effect

- Radiant energy absorbed at Earth's surface is eventually reradiated skyward. Because Earth has a much lower surface temperature than the Sun, its radiation is in the form of longwave infrared radiation. Because atmospheric gases, primarily water vapor and carbon dioxide, are more efficient absorbers of terrestrial (longwave) radiation, the atmosphere is heated primarily from the ground up.
- The greenhouse effect refers to the selective absorption of terrestrial radiation by atmospheric gases, mainly water vapor and carbon dioxide, that causes Earth's average temperature to be warmer than it would be otherwise.
- The greenhouse effect is a natural phenomenon that makes Earth habitable. It is often, but inaccurately, portrayed as the "villain" of global warming, but human activities that release greenhouse gases (primarily carbon dioxide) into the atmosphere actually cause climate change.

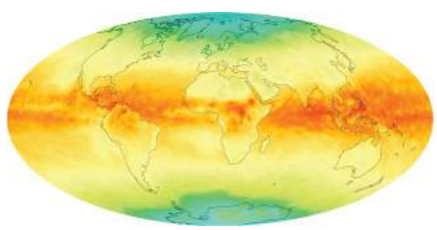
2.6 Earth's Energy Budget

LO 6 Describe the major components of Earth's annual energy budget.

Key Term

annual energy budget

- The annual balance of incoming and outgoing radiation is referred to as Earth's annual energy budget.
- A rather wide zone around the equator receives more solar radiation than is lost to space. The opposite is true for more poleward locations, where more heat is lost through outgoing longwave terrestrial radiation than is received. It is this energy imbalance between the low and high latitudes that drives the weather system and, in turn, transfers surplus heat from the tropics toward the poles.



Exercises and Online Activities

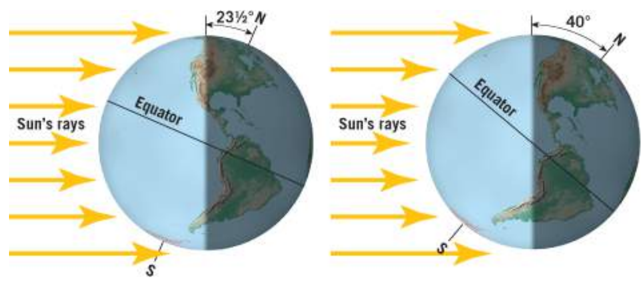
Mastering Meteorology™
For instructor-assigned homework, test prep resources, and other learning materials, visit **Mastering Meteorology.**

Review Questions

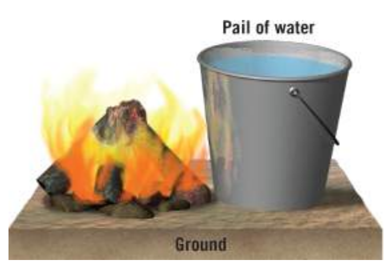
1. Explain why Earth's tilt on its axis causes seasons.
2. Define *solstice* and *equinox*, and give dates for the two solstices and two equinoxes.
3. If it is winter in the Northern Hemisphere, what season is it in the Southern Hemisphere?
4. Distinguish between kinetic energy and potential energy.
5. What is latent heat? Sensible heat?
6. Define *conduction*, *convection*, *advection*, and *radiation*.
7. Briefly describe the four laws of radiation.
8. What is meant by absorption of radiation? Transmission of radiation?
9. Define *scattering* and *reflection*.
10. What is diffused light?
11. What causes some clouds to appear white?
12. Define *albedo*.
13. How is solar radiation different from terrestrial radiation?
14. What is the atmospheric window?
15. Is the greenhouse effect a natural or human-made phenomenon?
16. List the ways Earth's surface gains and loses energy.
17. List the ways Earth's atmosphere gains and loses energy.

Give It Some Thought

1. Describe what the seasons would be like if Earth's axis were inclined 40° rather than 23½°, as is currently the situation. Where would the Tropics of Cancer and Capricorn be located? Where would the Arctic and Antarctic Circles be?



2. Is the Sun ever directly overhead anywhere in the United States? Justify your answer.
3. Do the annual variations in Earth–Sun distance adequately account for seasonal temperature changes? Explain.
4. During a "shore lunch" on a fishing trip to a remote location, the fishing guide will sometimes place a pail of lake water next to the cooking fire, as shown in the accompanying illustration. When the water in the pail begins to boil, the guide will lift the pail from the fire with one hand and "impress" the guests by placing the other hand on the bottom. Use what you have learned about the three mechanisms of heat transfer to explain why the guide's hand isn't burned by touching the bottom of the pail.



5. Draw simple sketch to show why the intensity of solar radiation striking Earth's surface changes when the Sun angle changes.
6. Rank *visible*, *infrared*, and *ultraviolet radiation* from longest to shortest wavelength and from most to least energetic.
7. Considering the fact that solar radiation travels in a straight line, explain why you can see an apple on the ground directly under an apple tree.
8. On what date is Earth closest to the Sun? On that date, what season is it in the Northern Hemisphere? Explain this apparent contradiction.
9. Which of the three mechanisms of heat transfer is most significant in each of the following situations:
    a. Driving a car with the seat heater turned on
    b. Sitting in an outdoor hot tub
    c. Lying inside a tanning bed
    d. Driving a car with the air conditioning turned on
10. The Sun shines continually at the North Pole for 6 months, from the spring equinox until the fall equinox, yet temperatures never get very warm. Explain why this is the case.
11. The accompanying image shows an area of our galaxy where stars having surface temperatures much hotter than the Sun have recently formed. Imagine that an Earth-like planet formed around one of these stars, at a distance where it receives the same intensity of light as Earth. Use the laws of radiation to explain why this planet may not provide a habitable environment for humans.

12. Rank the following according to the wavelength of radiant energy each emits, from the shortest wavelength to the longest:

- **a.** A light bulb with a filament glowing at 4000°C
- **b.** A rock at room temperature
- **c.** A car engine at 140°C

13. Figure 2.15 shows that about 30 percent of the Sun's energy is reflected or scattered back to space. If Earth's albedo were to increase to 50 percent, how would you expect Earth's average surface temperature to change?

14. Explain why Earth's equatorial regions are not becoming warmer, even though they receive more incoming solar radiation than they radiate back to space.

15. The accompanying photo shows the explosive 1991 eruption of Mount Pinatubo in the Philippines. How do you think global temperatures responded to the ash and debris this volcano spewed high into the atmosphere?

16. Complete each of the sentences below. Your answer choices for the first half of the sentence (before the comma) are *gas*, *liquid*, and *solid*. Your answer choices for the second half of the sentence are *absorbs* and *releases*. Your answer choices for the second sentence are *warms* and *cools*.

a. Evaporation is a phase change from _______________ to _______________, which _______________ latent heat. This _______________ the surrounding environment.

b. Condensation is a phase change from _______________ to _______________, which _______________ latent heat. This _______________ the surrounding environment.

c. Freezing is a phase change from _______________ to _______________, which _______________ latent heat. This _______________ the surrounding environment.

d. Melting is a phase change from _______________ to _______________, which _______________ latent heat. This _______________ the surrounding environment.

e. Sublimation is a phase change from _______________ to _______________, which _______________ latent heat. This _______________ the surrounding environment.

f. Deposition is a phase change from ______________ to ______________, which ______________ latent heat. This ______________ the surrounding environment.

By the Numbers

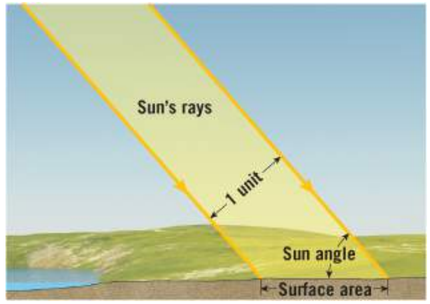
1. Refer to Figure 2.A in Box 2.1 and calculate the noon Sun angle on June 21 and December 21 at 50° north latitude, 0° latitude (the equator), and 20° south latitude. Which of these latitudes has the greatest variation in noon Sun angle between summer and winter?
2. For the latitudes listed in Problem 1, determine the length of daylight and darkness on June 21 and December 21 (refer to Table 2.1). Which of the latitudes listed has the largest seasonal variation in length of daylight? Which latitude has the smallest variation?
3. Calculate the noon Sun angle at your location for the equinoxes and solstices.
4. Using the accompanying figure and basic trigonometry, calculate the intensity of solar radiation. For simplicity, consider a solar beam of 1 unit width. The surface area over which the beam would be spread changes with Sun angle, such that:

   $$\text{Surface area} = \frac{1\text{ unit}}{\sin(\text{Sun angle})}$$

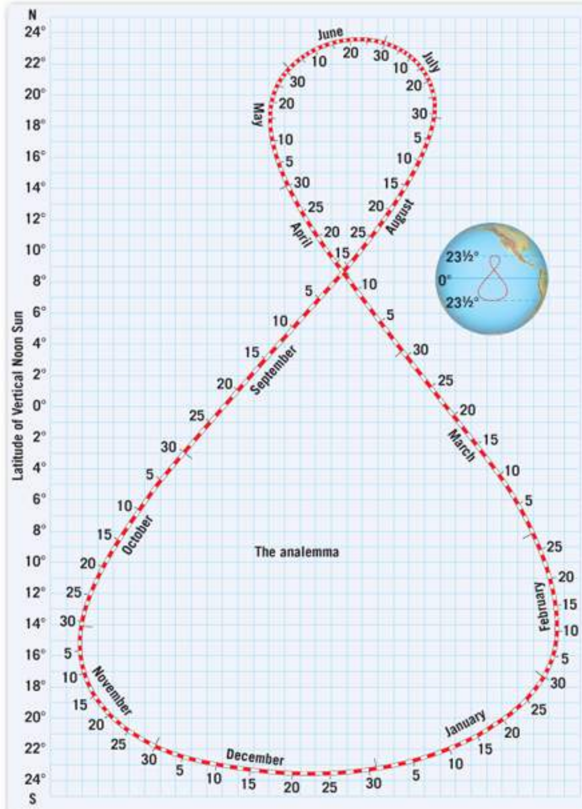
   Therefore, if the Sun angle at solar noon is 56°:

   $$\text{Surface area} = \frac{1\text{ unit}}{\sin 56^\circ} = \frac{1\text{ unit}}{0.829} = 1.260\text{ units}$$

   Using this method and your answers to Problem 3, calculate the intensity of solar radiation (surface area) for your location at noon during the summer and winter solstices. *Note:* Large surface areas equate to low solar intensities.



5. The accompanying analemma is a graph used to determine the latitude where the overhead noon Sun is located for any date. To determine the latitude of the overhead noon Sun from the analemma, find the desired date on the graph and read the coinciding latitude along the left axis. Determine the latitude of the overhead noon Sun for the following dates. Remember to indicate *north* (N) or *south* (S).
    a. March 21
    b. June 5
    c. December 10
6. Use Figure 2.A and the analemma used in Question 5 to calculate the noon Sun angle at your location (latitude) on the following dates:
    a. September 7
    b. July 5
    c. January 1



Latitude of Vertical Noon Sun
N
24°
22°
20°
18°
16°
14°
12°
10°
8°
6°
4°
2°
0°
2°
4°
6°
8°
10°
12°
14°
16°
18°
20°
22°
24°
S
June
July
May
April
August
September
March
October
February
November
December
January
The analemma
23½°
0°
23½°

Beyond the Textbook

1. Seasons in Tromso, Norway*

Activity A. Do an Internet search to answer the questions:

1. The University of Tromso, located in Tromso, Norway, is the world's northernmost university. What is the latitude of Tromso, to the nearest degree?
2. Where is Tromso located in relation to the Arctic Circle?

Activity B. Go to University of Tromso Weather Observations page at http://weather.cs.uit.no/. Click on "Weather Data History" to display the most recent 24 hours of data.

3. What are the maximum and minimum temperatures for this day?
4. Do you think the average daily temperatures will likely increase or decrease moving forward from this date?
5. What are the maximum and minimum amounts of solar radiation received on this day?

Change the date at the bottom of the page to display data for the most recent "summer solstice," and click on "Display Graph" to update.

6. What is the maximum temperature for this day?
7. Note that the temperature is given in degrees Celsius. Use Table A-3 to convert your summer solstice answer to degrees Fahrenheit.
8. What are the maximum and minimum amounts of solar radiation on this day?

Now change the date at the bottom of the page to display data for the "winter solstice," and click on "Display Graph" to update.

9. What is the maximum temperature for this day?
10. Note that the temperature is in degrees Celsius. Use Table A-3 to convert your winter solstice answer to degrees Fahrenheit.
11. What are the maximum and minimum amounts of solar radiation on this day?
12. What two factors explain much of the temperature differences that Tromso, Norway, experiences between the summer solstice and the winter solstice?

2. Earth's Energy Balance

Go to the Earthguide Global Energy Balance page at http://earthguide.ucsd.edu/earthguide/diagrams/energybalance/index.html, and click to read through the online tutorial.

1. Explain what happens to incoming sunlight (shortwave radiation) when it passes through the atmosphere.
2. Explain what happens to outgoing (longwave) radiation when it passes through the atmosphere.

* This activity was modified from Geosystems by Robert W. Christopherson.

Chapter 3 Temperature

This snow-capped mountain reminds us that temperatures decrease with an increase in altitude in the troposphere. Altitude is one of several factors that influence temperature.

Focus on Concepts

Each statement represents the primary learning objective for the corresponding major heading within the chapter. After you complete the chapter, you should be able to:

1. Calculate five commonly used types of temperature data and interpret a map that depicts temperature data using isotherms (3.1).
2. Discuss the basic daily and annual cycles of air temperature (3.2).
3. Name the principal controls of temperature and use examples to describe their effects (3.3).
4. Interpret the patterns depicted on world temperature maps (3.4).
5. Explain how different types of thermometers work and why the placement of thermometers is an important factor in obtaining accurate readings. Distinguish among Fahrenheit, Celsius, and Kelvin temperature scales (3.5).
6. Summarize several applications of temperature data (3.6).

Temperature is one of the basic elements of weather and climate. When someone asks what the weather is like outside, air temperature is often the first response. From everyday experience, we know that temperatures vary on different time scales: seasonally, daily, and even hourly. Moreover, we recognize that substantial temperature differences exist from one place to another. In Chapter 2 you learned how air is heated and examined the role of Earth–Sun relationships in causing temperature variations across seasons as well as across latitudes. In this chapter, you will examine several other factors that act as temperature controls. In addition, you will learn how temperature is measured and how temperature data can be useful. Applications of temperature data include evaluating energy consumption, measuring crop maturity, and expressing levels of human comfort.

3.1 For the Record: Air-Temperature Data

LO 1 Calculate five commonly used types of temperature data and interpret a map that depicts temperature data using isotherms.

Temperatures recorded daily at thousands of weather stations worldwide provide much of the temperature data compiled by meteorologists and climatologists. Hourly temperatures may be recorded by an observer or obtained from automated observation systems that continually monitor the atmosphere. At many locations, only the maximum and minimum temperatures are recorded.

Basic Calculations

A location's **daily mean temperature** is determined by averaging the 24 hourly readings or by adding the maximum and minimum temperatures for a 24-hour period and dividing by 2. From the maximum and minimum, the **daily temperature range** is computed by finding the difference between these figures. Other data involving longer periods are also compiled:

- The **monthly mean temperature** is calculated by adding together the daily means for each day of the month and dividing by the number of days in the month.
- The **annual mean temperature** is an average of the 12 monthly means.
- The **annual temperature range** is computed by finding the difference between the warmest and coldest monthly mean temperatures.

Mean temperatures are especially useful for making daily, monthly, and annual comparisons. It is common to hear a weather reporter state, "Last month was the warmest February on record," or "Today Denver was 10° warmer than Chicago." Temperature ranges are also useful statistics because they give an indication of extremes, a necessary part of understanding the weather and climate of a place or an area (Box 3.1).

Box 3.1

Hottest and Coldest Places in the United States

Most people living in the United States have experienced temperatures of 100°F or more. When statistics for the 50 states are examined, we find that every state has a maximum temperature record of 100°F or higher. Even Alaska has recorded a temperature this high—set June 27, 1915, at Fort Yukon, a town along the Arctic Circle in the interior of the state.

Maximum Temperature Records

The highest accepted temperature record for the United States—as well as the entire world—is 134°F. This long-standing record was set at Death Valley, California, on July 10, 1913. Summer temperatures at Death Valley are consistently among the highest in the Western Hemisphere. During June, July, and August, temperatures exceeding 120°F are to be expected. Fortunately, Death Valley has few human summertime residents (Figure 3.A).

Figure 3.A Almost a record!

On June 30, 2013, 100 years after Death Valley set the all-time high recorded temperature, it came close to equaling it. On that date, Death Valley's air temperature peaked at 129.2°F.

Why are summer temperatures at Death Valley so high? In addition to having the lowest elevation in the Western Hemisphere (53 meters [174 feet] below sea level), Death Valley is a desert. Although it is only about 300 kilometers (less than 200 miles) from the Pacific Ocean, mountains cut off the valley from the ocean's moderating influence and moisture.

Clear skies allow maximum solar radiation to strike the dry, barren surface. Because no energy is used to evaporate moisture, as occurs in humid regions, all the energy is available to heat the ground.

Minimum Temperature Records

We expect extremely cold temperatures during winter in high-latitude places that lack the moderating influence of the ocean. Further, we would expect stations located at high elevations to be especially cold. All these criteria apply to Prospect Creek, located north of the Arctic Circle in the Endicott Mountains of Alaska, which holds the record of –80°F. In the lower 48 states, the record of –70°F was set in the mountains at Rogers Pass, Montana, on January 20, 1954. Remember that many other places have experienced equally low or even lower temperatures, but these were not recorded at an official recording station.

Apply What You Know

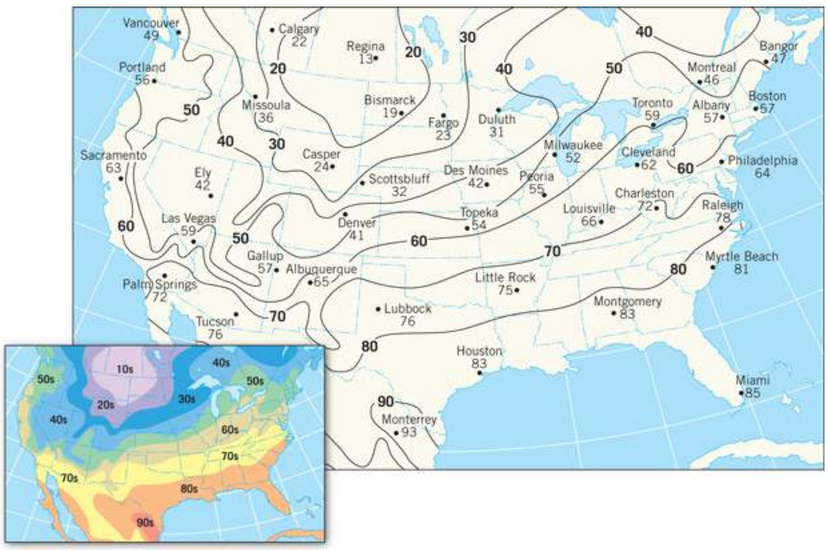
1. Death Valley is not a great distance from the cool Pacific Ocean yet experiences very high temperatures. Why is there no moderating ocean influence?
2. What factor might contribute to a record low temperature?

Isotherms

To display the distribution of air temperatures over large areas, *isotherms* are commonly used. An **isotherm** is a line that connects points on a map that have the same temperature (*iso* = equal, *therm* = temperature). Therefore, all points through which an isotherm passes have identical temperatures for the time period indicated. Generally, isotherms representing temperature differences of 5° or 10° are used, but *any* interval may be chosen. Figure 3.1 illustrates how isotherms are drawn on a map. Notice that most isotherms do not pass directly through the observing stations because the station readings may not coincide with the values chosen for the isotherms. Only an occasional weather station temperature will be exactly the same as the value of the isotherm, so it is usually necessary to draw the lines by estimating the proper position between observing stations.

Smartfigure 3.1 **Isotherms**

The large map shows high temperatures for a spring day. Isotherms are lines that connect points of equal temperature. Showing temperature distribution in this way makes patterns easier to see. On television and in many newspapers, temperature maps are in color, as shown in the inset map. Rather than label isotherms, these maps label the area *between* isotherms. For example, the zone between the 60°F and 70°F isotherms is labeled “60s.”



Watch **SmartFigure: Isotherm Maps**

Isothermal maps are valuable tools because they make temperature distribution clearly visible and make areas of low and high temperatures easy to identify. In addition, the amount of temperature change per unit of distance, called the **temperature gradient**, is easy to visualize. Closely spaced isotherms indicate a rapid rate of temperature change, whereas more widely spaced lines indicate a more gradual rate of change. For example, notice in Figure 3.1 that the isotherms are more closely spaced in Colorado and Utah (steeper temperature gradient), whereas the isotherms are spread farther apart in Texas (gentler temperature gradient). Without isotherms, a map would be covered with numbers representing temperatures at tens or hundreds of places, which would make patterns difficult to see.

> Isothermal maps make the distribution of temperature across a region visible at a glance.

You might have wondered . . .

What's the hottest city in the United States?

It depends on how you define "hottest." If average annual temperature is used, then Key West, Florida, is the hottest, with an annual mean of 78°F for the 30-year span 1981–2010. However, if we look at cities with the highest July maximums during the 1981–2010 span, then the desert community of Bullhead City, Arizona, has the distinction of being hottest. Its average daily high in July is a blistering 112°F!

Concept Checks 3.1

- How are the following temperature data calculated: daily mean, daily range, monthly mean, annual mean, and annual range?
- What are isotherms, and what is their purpose?

3.2 Cycles of Air Temperature

LO 2 Discuss the basic daily and annual cycles of air temperature.

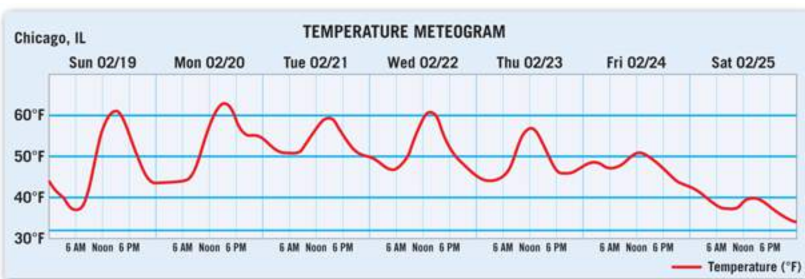
There are two basic cycles of air temperature—the rather predictable daily temperature cycle and the annual temperature cycle associated with the seasons.

Daily Temperature Cycle

You know from experience that a rhythmic rise and fall of air temperature occurs almost every day. This fact is confirmed when observing a **meteogram**, a graph that shows how meteorological variables change over time (Figure 3.2). During much of the February week recorded, the temperature curve follows the daily temperature cycle. It reaches a minimum around sunrise and then climbs steadily to a maximum between 1 P.M. and 4 P.M. The temperature then declines until sunrise the following day.

Figure 3.2 Meteogram showing temperatures in Chicago, Illinois

The typical daily rhythm, with minimums around sunrise and maximums in the afternoon, occurred on most days. The obvious exception occurred on February 25, when the maximum was reached at midnight and temperatures dropped throughout most of the day.

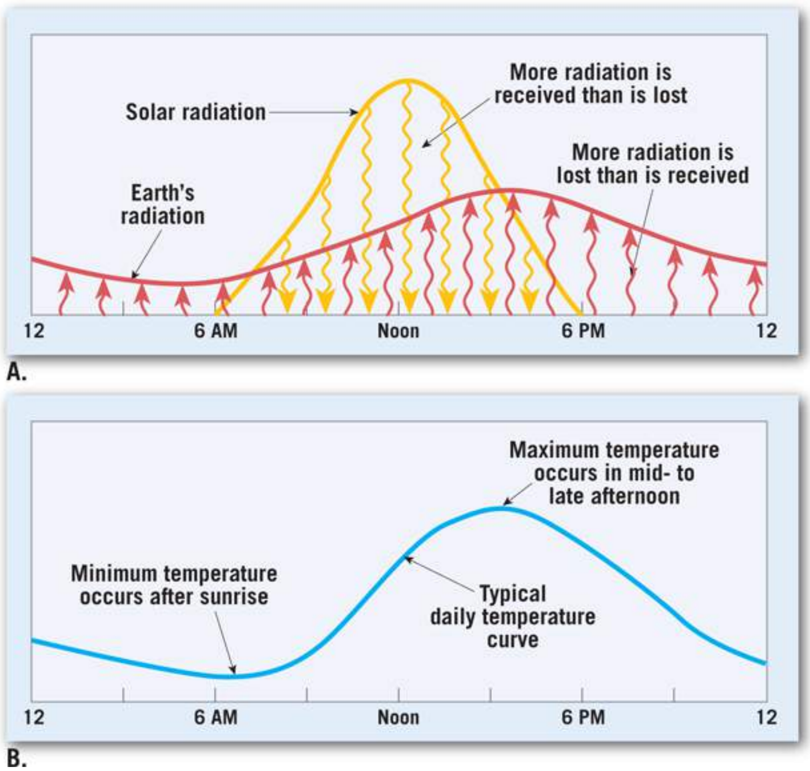


The primary control of the daily cycle of air temperature is Earth's daily rotation, which causes a location to move into daylight for part of each day and then into darkness. As the Sun's angle increases throughout the morning, the intensity of sunlight also rises, reaching a peak at noon and gradually diminishing in the afternoon. During the night, the atmosphere and the surface of Earth cool as they radiate away heat. The minimum temperature, therefore, occurs about the time of sunrise when the Sun again begins to heat the ground.

The daily variation of incoming solar energy versus outgoing Earth radiation and the resulting temperature curve for a typical middle-latitude location at the time of an equinox is shown in Figure 3.3A. It is apparent from this graph that the time of highest temperature does not generally coincide with the time of maximum solar heating. By comparing Figure 3.3A and Figure 3.3B, you can see that the greatest amount of solar radiation occurs at noon but that Earth continues to receive more energy than it emits until a few hours after noon. In other words, as long as the amount of solar energy gained exceeds the amount of Earth radiation lost, the air temperature continues to rise. When the incoming solar energy no longer exceeds the rate of energy lost by Earth, the temperature begins to fall.

Figure 3.3 The daily cycle of incoming solar radiation, Earth's radiation, and the resulting temperature cycle

This example is for a midlatitude site around the time of an equinox. **A.** As long as solar energy gained exceeds outgoing energy emitted by Earth, the temperature rises. When outgoing energy from Earth exceeds the input of solar energy, temperature falls. **B.** Note that the daily temperature cycle *lags* behind the solar radiation input by a couple of hours.



> The lowest daily temperature generally occurs at sunrise and highest daily temperature occurs in the mid- to late afternoon.

In dry regions, particularly on cloud-free days, the amount of radiation absorbed by the surface is generally high. Therefore, the maximum temperature at these locales often occurs quite late in the afternoon. Humid locations, in contrast, frequently experience a shorter time lag in the occurrence of their temperature maximum.

Although the rise and fall of daily temperatures usually reflects the general rise and fall of incoming solar radiation, this is not always the case. For example, a glance back at Figure 3.2 shows that on February 25, the maximum temperature occurred at midnight, after which temperatures fell throughout most of the day. If temperature records for a station are examined for a period of several weeks, apparently random variations are seen. Such irregularities are caused primarily by the passage of atmospheric disturbances (weather systems) that are often accompanied by variable cloudiness and winds that bring air having contrasting temperatures. Under these circumstances, the maximum and minimum temperatures may occur at any time of the day or night.

Annual Temperature Cycle

People who live in the tropics are accustomed to regularly warm temperatures. However, if you live in the midlatitudes you are familiar with warm, or even hot, summers and rather cool winters. As you move to even higher latitudes, this seasonal temperature cycle becomes more pronounced. For example, the average annual range of temperature is about 24°C (43°F) in Albuquerque, New Mexico, whereas the annual temperature range in Fairbanks, Alaska, located near the Arctic Circle, is about 40°C (72°F), nearly twice that of Albuquerque.

> The seasonal temperature cycle becomes more pronounced the farther you get from the equator.

In most years, the months with the highest and lowest mean temperatures do not coincide with the periods of maximum and minimum incoming solar radiation. North of the tropics, the greatest intensity of solar radiation occurs at the time of the summer solstice in June, yet the months of July and August are generally the warmest of the year in the Northern Hemisphere. Conversely, the least amount of solar energy is received in December at the time of the winter solstice, but January and February are usually colder.

> The highest and lowest mean temperatures do not coincide with the periods of maximum and minimum incoming solar radiation.

In the United States, the annual temperature cycle lags behind the period of the most intense solar heating by an average of 27 days. However, in areas located near a large body of water, the average lag time is 36 days. Midwestern St. Louis, for example, usually experiences its highest temperatures in July, whereas coastal San Francisco experiences its warmest temperatures typically in September, but occasionally as late as October. San Francisco's extended lag in temperature is primarily due to the fact that large water bodies take much longer to heat up than land, a phenomenon discussed in detail in the next section.

Concept Checks 3.2

- Although the intensity of incoming solar radiation is greatest at noon, the warmest part of the day is most often mid-afternoon. Why?
- Explain why the times of the year when a location experiences its highest and lowest temperatures do not coincide with occurrences of maximum and minimum annual solar radiation.

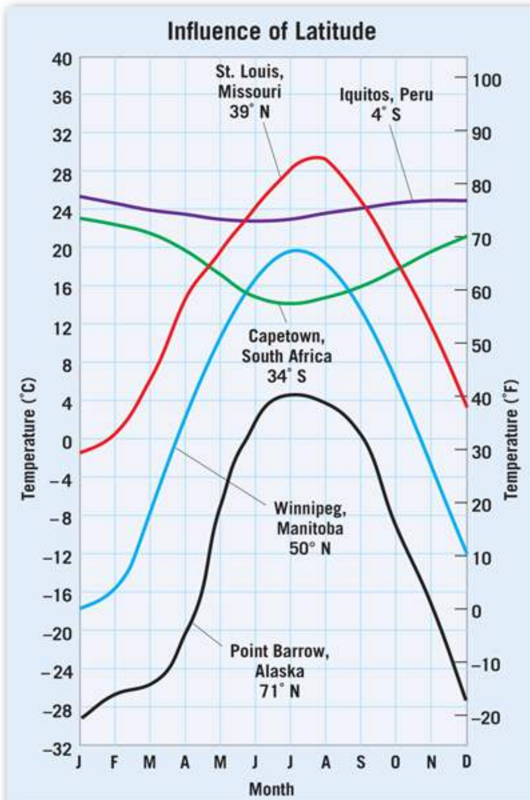
3.3 Why Temperatures Vary

LO 3 Name the principal controls of temperature and use examples to describe their effects.

A **temperature control** is any factor that causes temperatures to vary. The primary control of temperature is *latitude*. Recall from Chapter 2 that latitude determines the annual variations in Sun angle and length of daylight, which causes warmer temperatures in the tropics and colder temperatures at the poles. As the Sun's vertical rays migrate during the year, they produce the seasonal temperature changes we observe each year. Figure 3.4 shows the annual temperature cycle for several different locations and reminds us of the importance of latitude as a control of temperature and seasonal temperature variations.

Figure 3.4 **Latitude is the major control of temperature**

The data for these five cities remind us that latitude (Earth–Sun relationships) is a significant factor influencing temperature.



> The primary control of temperature is latitude because it determines the annual variations in Sun angle and length of daylight.

But latitude is not the only control of temperature. If it were, we would expect all places along the same line of latitude to have identical temperatures, which is clearly not the case. For instance, Eureka, California, and New York City are both coastal cities at about the same latitude, and both have the same annual mean temperature of 11°C (about 52°F). Yet New York City averages 9°C (17°F) warmer than Eureka in July and 9°C (17°F) colder than Eureka in January. To explain these differences and countless others, we must acknowledge that factors other than latitude strongly influence temperature.

Elevation

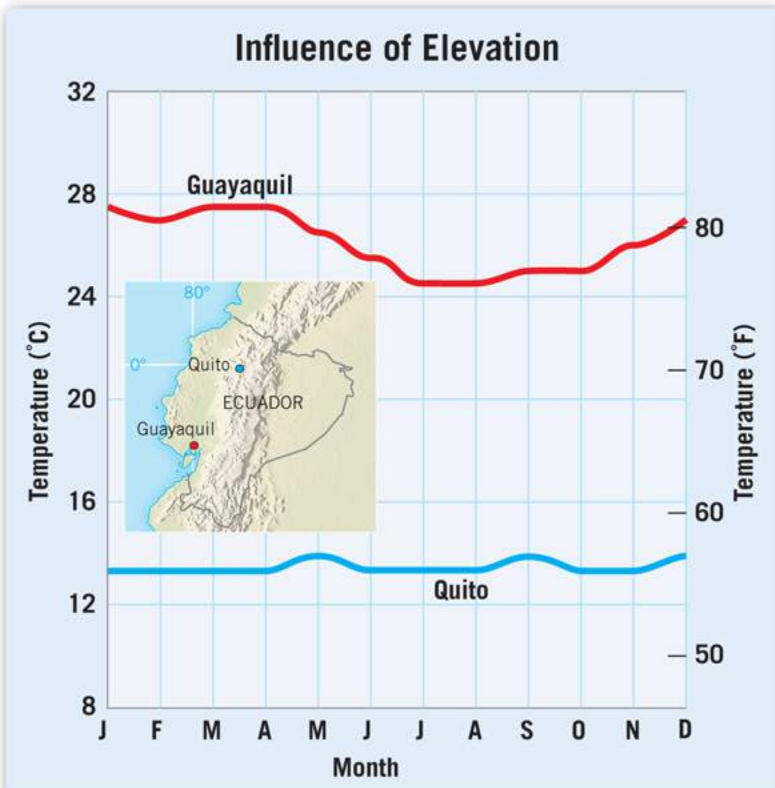
Recall that temperatures on average decrease with an increase in altitude in the troposphere. As a result, some mountaintops are snow covered year-round (Figure 3.5). Two cities in Ecuador, Quito and Guayaquil, demonstrate the influence of altitude on mean temperature (Figure 3.6). Both cities are located near the equator and relatively close to one another, but the annual mean temperature at Guayaquil is about 26°C (80°F), compared with Quito's mean of half that value, 13°C (56°F). What explains the difference? Guayaquil is located near sea level, whereas Quito is high in the Andes Mountains, at 2800 meters (9200 feet).

Figure 3.5 Cold mountaintop

In the troposphere, temperatures generally decrease as altitude increases. As a result, some mountaintops are snow covered all year.

Figure 3.6 Monthly mean temperatures for Quito and Guayaquil, Equador

Both cities are located near the equator. However, because Quito is high in the Andes, at 2800 meters (9200 feet), it experiences much cooler temperatures than Guayaquil, which is located near sea level.



> Besides latitude, elevation is the strongest control of air temperature.

Elevation significantly affects not only mean temperatures, but also the daily temperature range. Temperatures drop as altitude increases, and atmospheric pressure and density also diminish. Because air is thinner at high altitudes, the overlying atmosphere absorbs, reflects, and scatters a *smaller portion* of the incoming solar radiation. Consequently, with an increase in altitude, the intensity of solar radiation increases, resulting in rapid daytime heating. Conversely, nighttime cooling also occurs at an accelerated rate. Therefore, observing stations located high in the mountains generally have a greater daily temperature range than do stations at lower elevations.

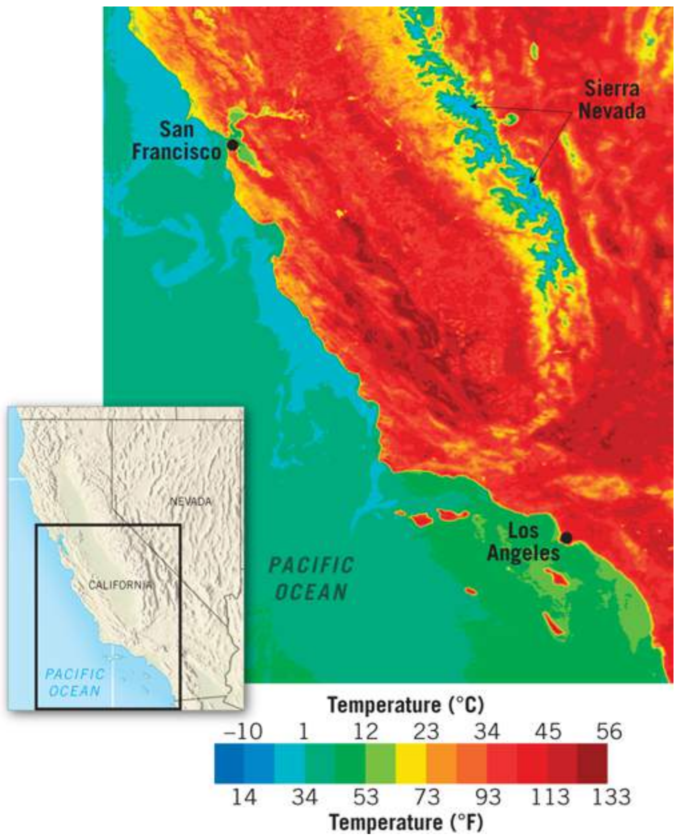
Elevation clearly modifies temperatures, but the annual temperature range (difference between the warmest and coldest monthly mean temperatures) is not strongly affected. The monthly mean temperatures are lower throughout the year at higher elevations, but the annual temperature range would be similar to a location at lower elevation, all other factors being equal.

Land and Water

Recall that the heating of Earth's surface controls, to a large degree, the heating of the air above it. Therefore, to understand variations in air temperature, we must understand the variations in heating properties of different surfaces—soil, water bodies, forests, ice, and so on. Different land surfaces reflect and absorb varying amounts of incoming solar energy, which in turn cause variations in the temperature of the air above. The greatest contrast, however, is not between different land surfaces but rather between land and water, as illustrated in Figure 3.7. This satellite image shows surface temperatures in portions of California, Nevada, and the adjacent Pacific Ocean on the afternoon of May 2, 2004, during a spring heat wave. Land-surface temperatures, shown mainly in red, are clearly much higher than water-surface temperatures. The peaks of the Sierra Nevada, still capped with snow, form a cool blue band down the eastern side of California.

Figure 3.7 Differential heating of land and water

This satellite image shows land- and water-surface temperatures (not air temperatures) for the afternoon of May 2, 2004. Water-surface temperatures in the Pacific Ocean are much lower than land-surface temperatures in California and Nevada. The narrow band of cool temperatures in the center of the image is associated with snow-capped mountains.



For large bodies of land and water, such as those shown in Figure 3.7, land heats more rapidly and to higher temperatures than water and, conversely, cools more rapidly and to lower temperatures than water. Why do land and water heat and cool differently? Several factors are responsible:

1. An important reason that the surface temperature of water rises and falls much more slowly than the surface temperature of land

is that *water is highly mobile*. As water is heated, convective flow distributes the heat through a considerably larger mass. In contrast, heat does not penetrate deeply into soil or rock; it remains concentrated near the surface. Obviously, no mixing can occur on land because it is not fluid. Instead, heat must be transferred by the slow process of conduction. During winter, the shallow layer of rock and soil that was heated in summer cools rapidly. Water bodies, in contrast, cool slowly as they draw on the reserve of heat stored within. As the water surface cools, the chilled surface water, which is dense, sinks and is replaced from below by warmer water, which is less dense. Consequently, a larger mass of water must cool before the temperature at the surface will drop appreciably.

> Variations in air temperatures are much greater over land than over water.

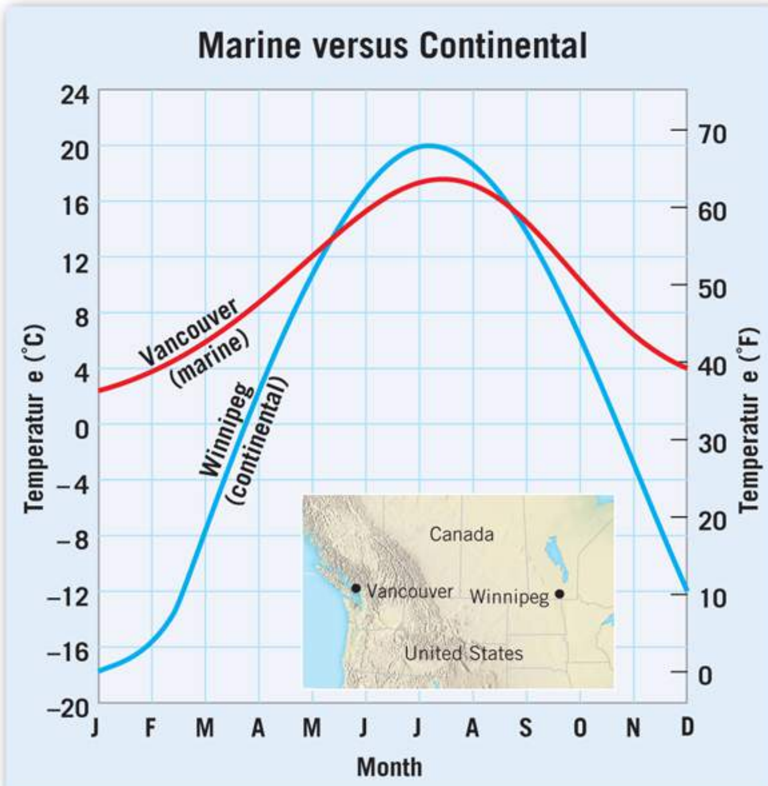
2. Because land surfaces are opaque, heat is absorbed only at the surface. This fact is easily demonstrated at a beach on a hot summer afternoon by comparing the surface temperature of the sand to the temperature just a few centimeters beneath the surface. Water, being more transparent, allows some solar radiation to penetrate to a depth of several meters.
3. The **specific heat**—the amount of heat needed to raise the temperature of 1 gram of a substance by 1°C—is more than three times greater for water than for land. Thus, considerably more heat is required to raise the temperature of water the same amount as an equal volume of land.
4. Evaporation (a cooling process) from water bodies is greater than from land surfaces. Energy is required to evaporate water. When energy is used for evaporation (latent heat), it does not raise the temperature (sensible heat).

Collectively, these factors cause water to warm more slowly, store greater quantities of heat, and cool more slowly than land.

Monthly temperature data for two cities demonstrate the moderating influence of a large water body and the more extreme seasonal temperatures associated with land-locked locations (Figure 3.8). Vancouver, British Columbia, is a maritime city located along the windward Pacific coast, whereas Winnipeg, Manitoba, is far from the influence of water. Both cities are at about the same latitude and thus experience similar Sun angles and lengths of daylight throughout the year. Vancouver, however, has a mean January temperature that is 20°C (36°F) warmer than Winnipeg's and a July mean temperature that is 2.6°C (4.7°F) cooler than Winnipeg's. The key to Vancouver's moderate year-round climate is the influence of the Pacific Ocean.

Smartfigure 3.8 Mean monthly temperatures for Vancouver, British Columbia, and Winnipeg, Manitoba

Vancouver has a much smaller annual temperature range because of the strong marine influence of the Pacific Ocean. Winnipeg illustrates the greater extremes associated with an interior, or continental, location.



Watch **SmartFigure: Maritime Temperatures**

On a different scale, the moderating influence of water may also be demonstrated when temperature variations in the Northern and Southern Hemispheres are compared. The views of Earth in Figure 3.9 show the uneven distribution of land and water over the globe. Water covers 61 percent of the Northern Hemisphere; land represents the remaining 39 percent. However, the figures for the Southern Hemisphere (81 percent water and 19 percent land) reveal why it is correctly called the "water hemisphere." Table 3.1 portrays the considerably smaller annual temperature ranges in the water-dominated Southern Hemisphere compared with the Northern Hemisphere.

Figure 3.9 **North versus south**

These views of Earth show the uneven distribution of land and water between the **A.** Northern and **B.** Southern Hemispheres. Almost 81 percent of the Southern Hemisphere is covered by the oceans—20 percent more than the Northern Hemisphere.

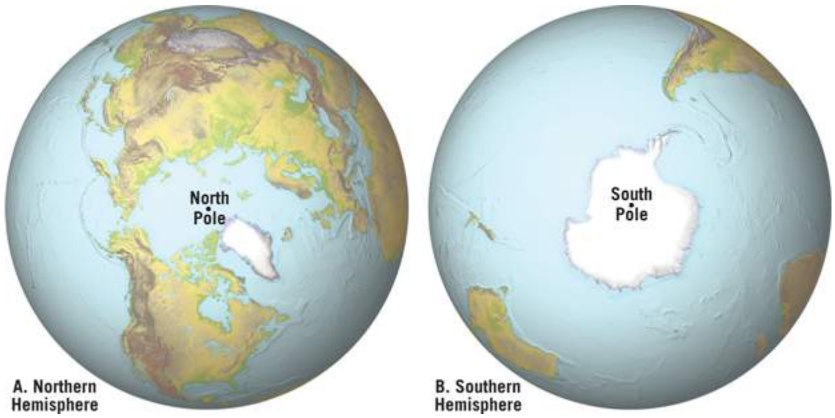


Table 3.1 **Variations in Annual Mean Temperature Range (°C) with Latitude**

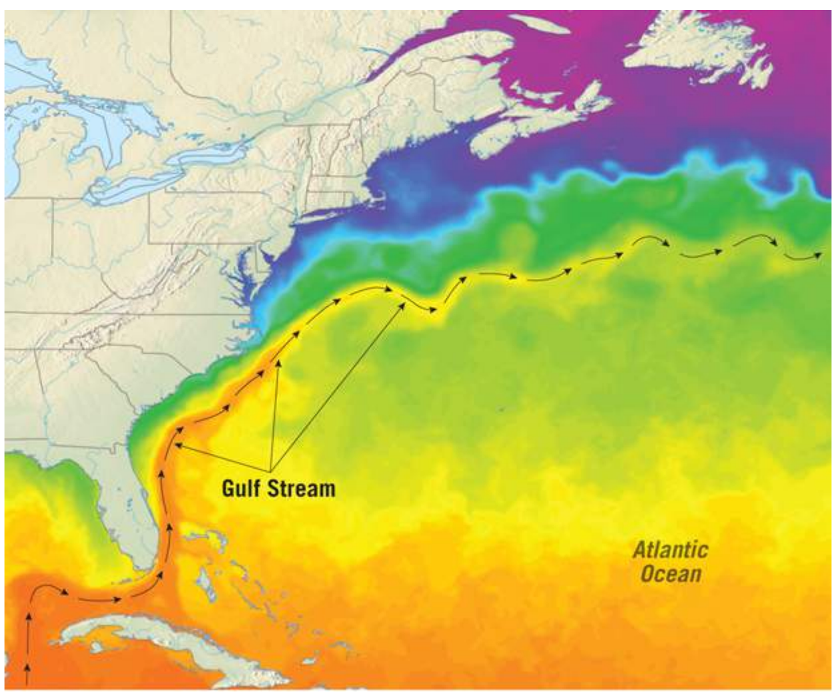
Latitude	Northern Hemisphere	Southern Hemisphere
0	0	0
15	3	4
30	13	7
45	23	6
60	30	11
75	32	26
90	40	31

Ocean Currents

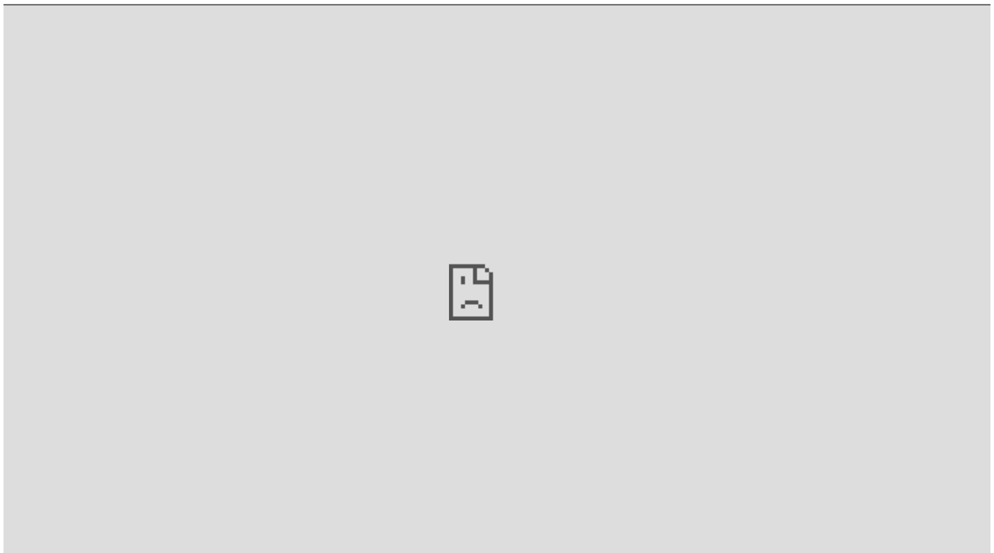
The Gulf Stream is an important surface current in the Atlantic Ocean that flows northward along the East Coast of the United States (Figure 3.10). Surface currents like this one are set in motion by the wind. At the water surface, energy is passed from moving air to the water through friction. The resulting drag exerted by winds blowing steadily across the ocean causes the surface layer of water to move. Thus, major horizontal movements of surface waters are closely related to the circulation of the atmosphere.

Figure 3.10 The Gulf Stream

In this satellite image off the east coast of the United States, red represents higher water temperatures, and blue represents cooler water temperatures. The current transports heat from the tropics far into the North Atlantic.



Watch **Animation: The Gulf Stream**



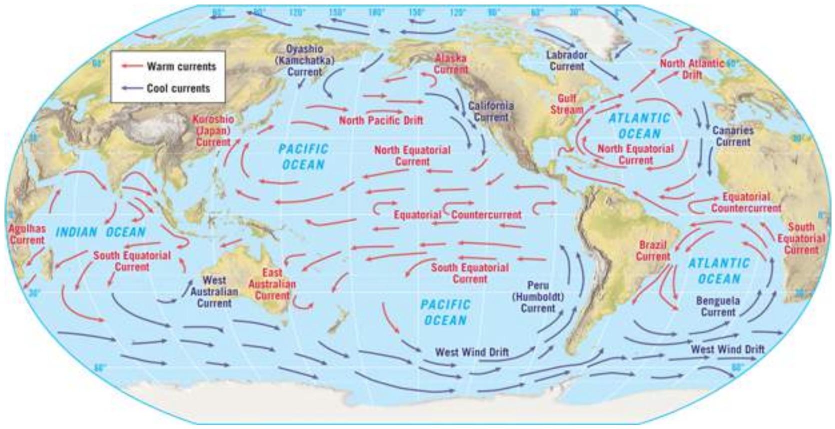
The atmospheric circulation that produces the ocean currents is driven by the unequal heating of Earth by the Sun. Recall from Chapter 2 that there is a net gain of incoming solar radiation in the tropics and a net loss at the poles. Because the tropics are not becoming progressively warmer, nor are the polar regions becoming colder, there must be a large-scale transfer of heat from areas of excess heat energy to areas of deficit. This is indeed the case.

> The transfer of heat by winds and ocean currents is nature's attempt to equalize the latitudinal energy imbalance between the tropics and the poles.

Ocean water movements account for about one-quarter of this total heat transport, and winds account for the remaining three-quarters (Figure 3.11).

Figure 3.11 Major surface-ocean currents

Poleward-moving currents are warm, and equatorward-moving currents are cold. Surface-ocean currents are driven by global winds and play an important role in redistributing heat around the globe.



Watch Video: Fluctuations in Sea-Surface Temperature

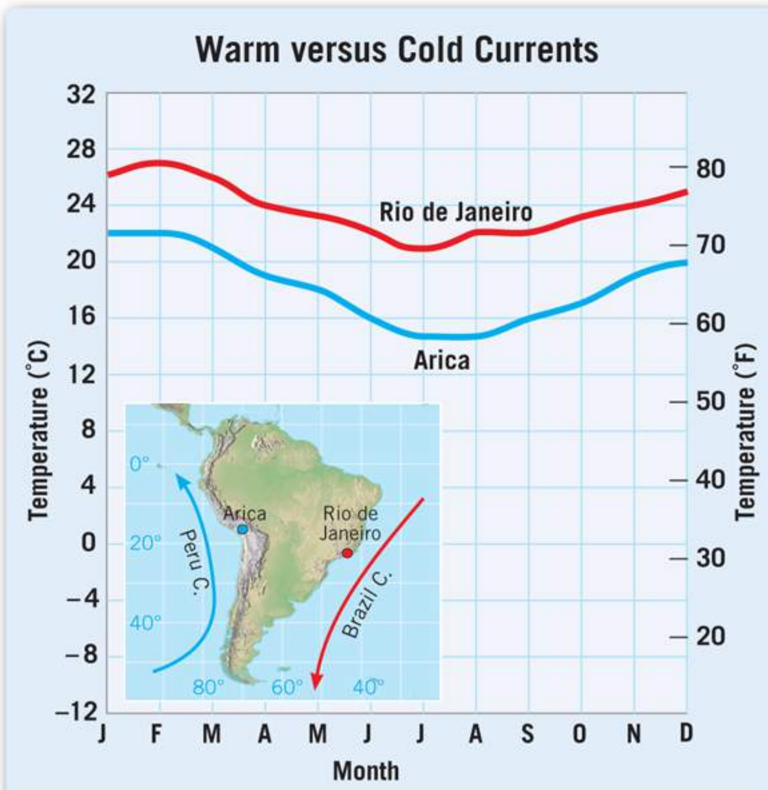
Watch **Animation: Ocean Circulation Patterns**

Surface-ocean currents have an important effect on climate. The moderating effect of poleward-moving warm ocean currents is well known. The North Atlantic Drift, an extension of the warm Gulf Stream, keeps wintertime temperatures in Great Britain and much of Western Europe warmer than would be expected for their latitudes (see Figure 3.11).

In contrast to *warm ocean currents*, the effects of which are most apparent during the winter, *cold currents* exert their greatest influence in the tropics or, during the summer months, in the middle latitudes. For example, the cool Peru Current off the west coast of South America moderates the tropical heat along this coast. As shown in Figure 3.12, Arica, Chile, a town adjacent to the cold Peru current, is about 8°C (13°F) cooler in summer than Rio de Janeiro, Brazil. Closer to home, the cold California Current keeps summer temperatures in subtropical coastal southern California 6°C (about 11°F) cooler on average than temperatures recorded at east coast stations at the same latitude.

Figure 3.12 **The chilling effect of a cold current verses a warm current**

Monthly mean temperatures for Rio de Janeiro, Brazil, and Arica, Chile. Both are coastal cities near sea level. Even though Arica is closer to the equator than Rio de Janeiro, its temperatures are cooler. Arica is influenced by the cold Peru Current, whereas Rio de Janeiro is adjacent to the warm Brazil Current.

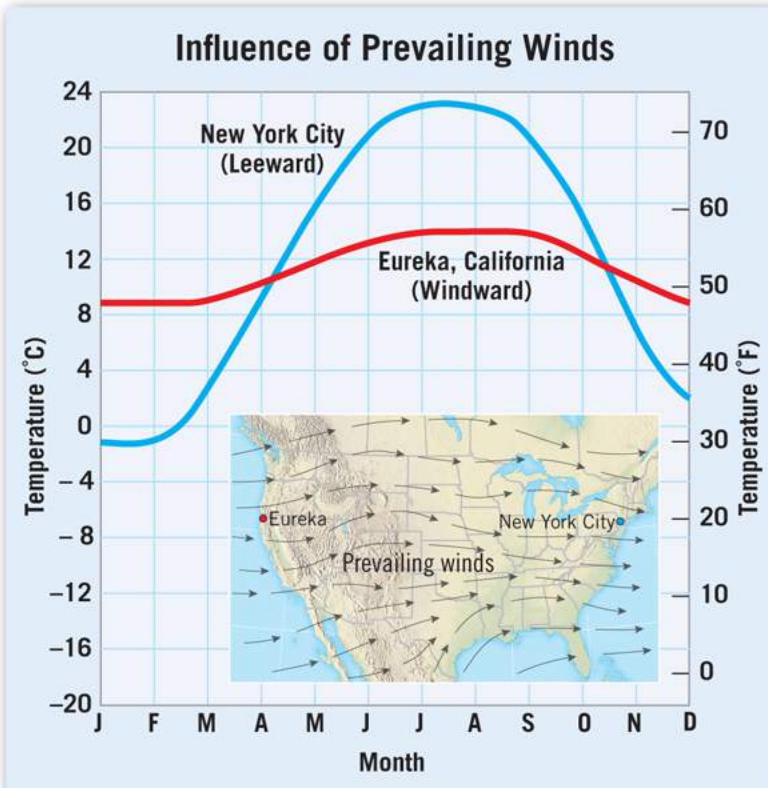


Geographic Position and Prevailing Wind Direction

The effects of differential heating of land and water can be blown inland by the *prevailing wind* at a particular location. A coastal station where prevailing winds blow from the ocean onto the shore (a *windward* coast) observes considerably different temperatures from those observed by a coastal location where prevailing winds blow from the land toward the ocean (a *leeward* coast). In the first situation, the windward coast experiences the full moderating influence of the ocean—cooler summers and milder winters. A station on a leeward coast at the same latitude would experience a much larger annual temperature range. Eureka, California, and New York City, two cities mentioned earlier, illustrate this aspect of geographic position (Figure 3.13). The prevailing winds in the midlatitudes flow from west to east and are called the *westerlies*. Because Eureka is strongly influenced by prevailing westerly winds from the ocean and New York City is not, the annual temperature range at Eureka is much smaller.

Figure 3.13 Monthly mean temperatures for Eureka, California, and New York City

Both cities are coastal and located at about the same latitude. Because Eureka is strongly influenced by prevailing winds from the ocean and New York City is not, the annual temperature range at Eureka is much smaller.

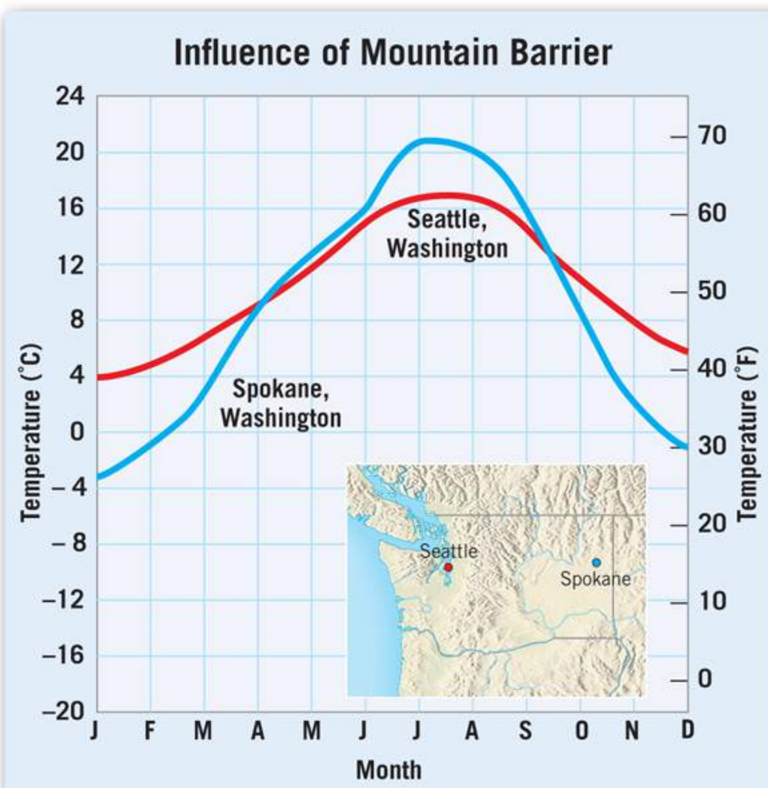


If there is an ocean current along the coast, then the moderating effect of the ocean current can also be blown inland. Because of the prevailing westerly winds, the moderating effects of the North Atlantic Drift are carried far inland. For example, the January mean in London is almost 5°C (8°F) higher than in New York City, which lies 13° latitude farther south than London.

Prevailing winds can also affect temperatures if the winds blow across a mountain range, where the mountains create a barrier from the moderating effects of the ocean. Seattle and Spokane, both in the state of Washington, illustrate this aspect of geographic position. Although Spokane is only about 360 kilometers (225 miles) east of Seattle, the towering Cascade Range effectively cuts off Spokane from the moderating influence of the Pacific Ocean. Consequently, Seattle's temperatures show a marked marine influence, whereas Spokane's are more typically continental (Figure 3.14). Seattle is 7°C (13°F) warmer than Spokane in January and 4°C (7°F) cooler than Spokane in July. The annual temperature range at Spokane is 11°C (nearly 20°F) greater than in Seattle.

Figure 3.14 Monthly mean temperatures for Seattle and Spokane, Washington

Because the Cascade Mountains cut off Spokane from the moderating influence of the Pacific Ocean, its annual temperature range is greater than Seattle's.



Mountains not only act as barriers to airflow, but also influence temperatures in other ways. The windward (*upslope*) side of a mountain tends to be cooler, while the leeward (*downslope*) side tends to be warmer. One example of the influence of mountains on temperature is found in the southwestern United States. Winds blowing onshore along the California coast keep temperatures relatively moderate. These winds then travel up and over a large mountain belt and descend into eastern California, Nevada, and Arizona. The air coming down the mountain warms by compression as it descends. Consequently, the air reaching the leeward side of the mountain is much warmer than the air on the windward side. The *adiabatic processes* that produces this phenomenon will be discussed in more detail in the next chapter.

Eye on the Atmosphere 3.1

Imagine being at this beach on a warm, sunny summer afternoon.

Apply What You Know

1. Describe the temperatures you would expect if you measured the beach surface and then at a depth of 12 inches.
2. If you stood waist deep in the water and measured the water's surface temperature and the temperature at a depth of 12 inches, how would these measurements compare to those taken on the beach?

Albedo Variations

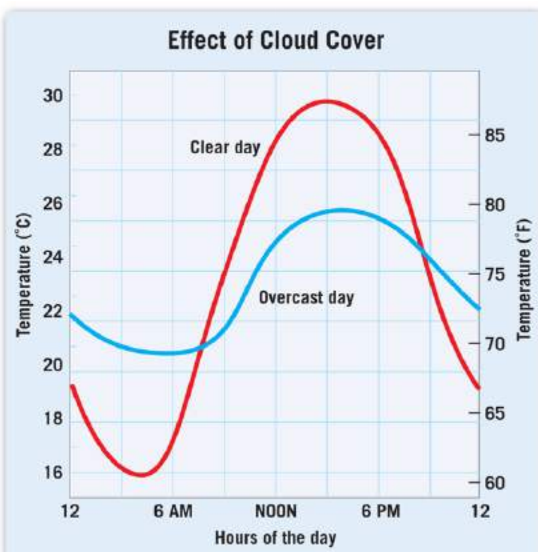
Recall that *albedo* refers to the fraction of radiation reflected by an object. Also recall that solar radiation reflected back to space is lost to Earth and does not play a role in heating Earth's surface and atmosphere. Thus, any increase in albedo reduces the amount of energy available to heat the atmosphere. Conversely, a decrease in albedo means an increase in the quantity of energy absorbed by Earth's surface and available to heat the atmosphere.

Cloud Cover

You may have noticed that clear days are often warmer than cloudy ones. This demonstrates that cloud cover is an important control of temperature because clouds reflect some of the sunlight that strikes them. Because cloud cover reduces the amount of incoming solar radiation, daytime temperatures are lower than if the sky were clear (Figure 3.15). The albedo of clouds depends on the thickness of the cloud cover and can vary from 25 to 90 percent (see Figure 2.17).

Smartfigure 3.15 The daily cycle of temperature at Peoria, Illinois, for two July days

Clouds reduce the daily temperature range. During daylight hours, clouds reflect solar radiation back to space. Therefore, the maximum temperature is lower than if the sky were clear. At night, the minimum temperature will not fall as low because clouds retard the loss of heat.



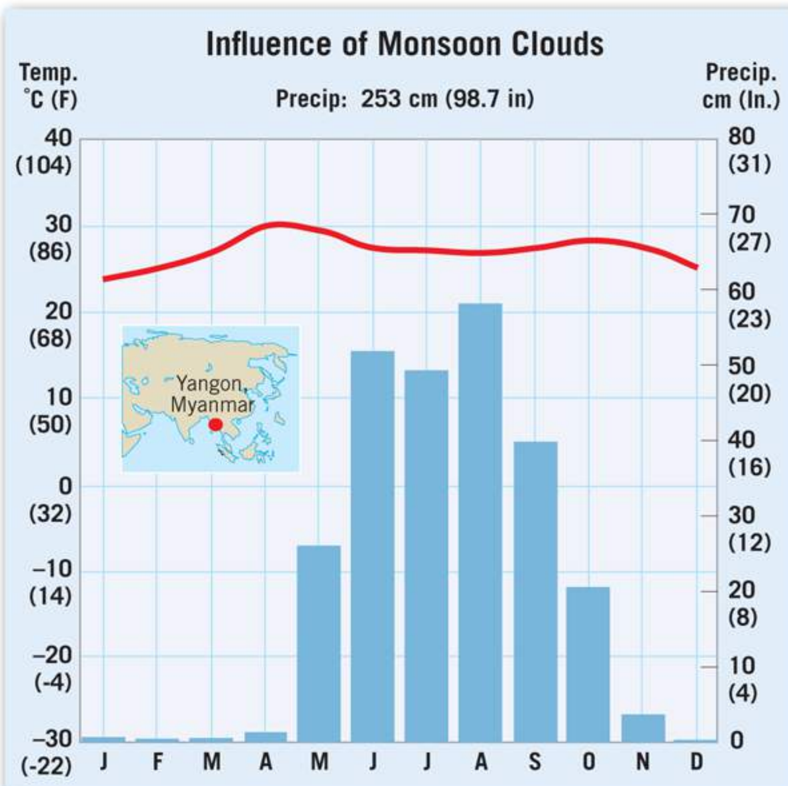
Watch SmartFigure: Cloudy vs. Clear Days

At night, clouds have the opposite effect. They absorb outgoing Earth radiation and emit a portion of it back toward the surface. Thus, nighttime air temperatures do not drop as dramatically as they would on a clear night. The effect of cloud cover is to reduce the daily temperature range by lowering the daytime maximum and raising the nighttime minimum, as illustrated by the graph in Figure 3.15.

Extensive periods of cloud cover can also reduce temperatures sufficiently in some locations to disrupt the seasonal cycle of temperatures. For example, each year much of southern Asia experiences an extended period of heavy monsoon rains. (This pattern is associated with the monsoon circulation and is discussed in Chapter 7.) The graph for Yangon, Myanmar (Burma), illustrates this pattern (Figure 3.16). Notice that the highest monthly mean temperatures occur in April and May, before the summer solstice, rather than in July and August as normally occurs at most stations in the Northern Hemisphere. This is because the extensive cloud cover during the summer months, when we would usually expect temperatures to climb, increases the albedo of the region and reduces incoming solar radiation at the surface. As a result, the highest monthly mean temperatures occur in late spring, when the skies are still relatively clear.

Figure 3.16 The influence of monsoon clouds

Monthly mean temperatures (line graph) and monthly mean precipitation (bar graph) for Yangon, Myanmar. The highest mean temperature occurs in April, just before the onset of heavy summer rains. The abundant cloud cover associated with the rainy period reflects back to space the solar energy that otherwise would strike the ground and raise summer temperatures.



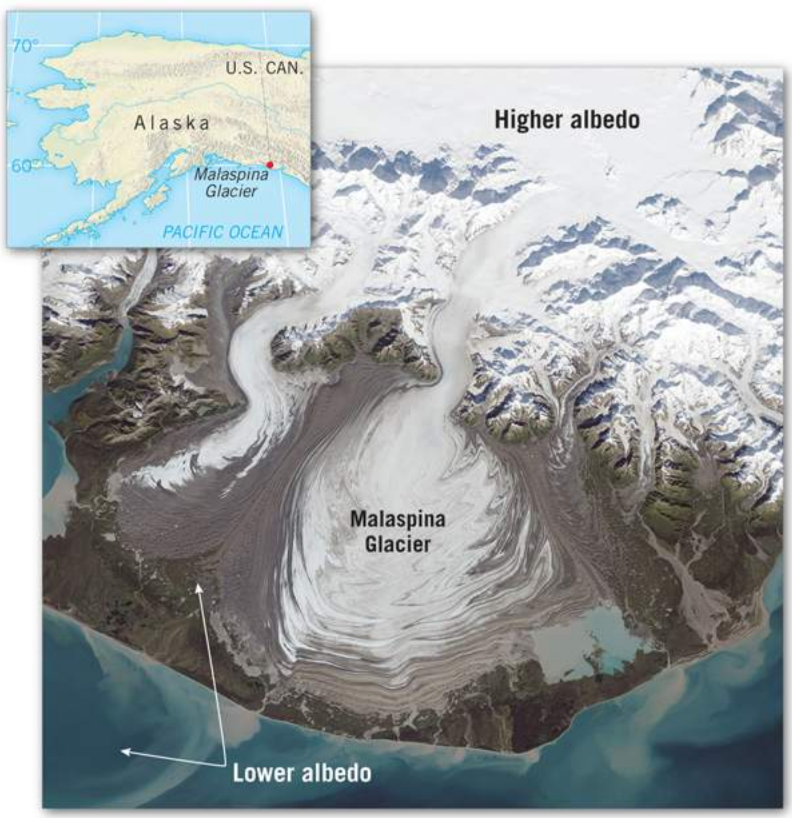
> The effect of cloud cover is to reduce the daily temperature range by lowering the daytime maximum and raising the nighttime minimum.

Influence of Snow and Ice

Snow- and ice-covered surfaces have high albedos. This is why snow covering the ground keeps daytime temperatures on a sunny day cooler than they would be otherwise. This idea is illustrated in Figure 3.17. The incoming solar energy is reflected by the snow and lost rather than absorbed by the ground and heating the lower atmosphere.

Figure 3.17 Contrasting albedos

Ice- and snow-covered surfaces have high albedos, thus keeping air temperatures lower than if the surface were not highly reflective. This image shows Malaspina Glacier in Alaska.



Large portions of the Arctic Ocean are covered by sea ice—frozen seawater that floats because it is less dense than liquid water. As you would expect, the area covered by sea ice changes with the seasons, expanding in winter and contracting in summer. Monitoring since the late 1970s has also shown that, over the years, the area covered by sea ice is shrinking. Thus, broad zones that were once covered by highly reflective ice are being replaced by the darker ocean surface that reflects less and absorbs more. The lowering of albedo in the Arctic is contributing to rising temperatures in this region, a topic that will be addressed in more detail in Chapter 14.

Other Factors Influencing Temperature

Many local, as well as weather-related, factors influence the temperature of a location. One local factor is the type of surface that predominates. For example, areas that are heavily vegetated tend to have cooler average summer temperatures than sparsely vegetated arid regions. Shade and transpiration by plants absorb large quantities of heat from the surface. This idea is exemplified by cities in the eastern United States, such as Atlanta, Georgia, that have significantly higher summer temperatures than the surrounding forested rural areas. This phenomenon, called the *urban heat island*, is considered in more detail in Box 3.2.

Box 3.2

How Cities Influence Temperature: The Urban Heat Island

One of the best-documented human impacts on climate is termed the *urban heat island*, a phenomenon in which the built environment alters a city's air temperature. The construction of factories, roads, office buildings, and houses creates new microclimates of great complexity. Changes in the way cities absorb and emit radiation generally increase temperatures compared to surrounding rural areas.

> Temperatures in cities are generally higher than in nearby rural areas.

Why are cities warmer than rural areas? The radical change in the surface that results when rural areas are transformed into cities is a significant cause of an urban heat island. Large stone and steel buildings, combined with concrete and asphalt city parking lots, absorb and store greater quantities of solar radiation than do the trees and farmland typical of many rural areas (Figure 3.B). In addition, these impermeable city surfaces cause rapid runoff of rainwater, resulting in a significant reduction in the evaporation rate. Hence, heat energy that would have been used to convert liquid water to a gas now goes to further increase the surface temperature. At night, as both the city and countryside cool by radiative losses, the stone-like surface of the city gradually releases the additional heat accumulated during the day, keeping the urban air warmer than that of the outlying areas.

Figure 3.B Downtown Atlanta, Georgia

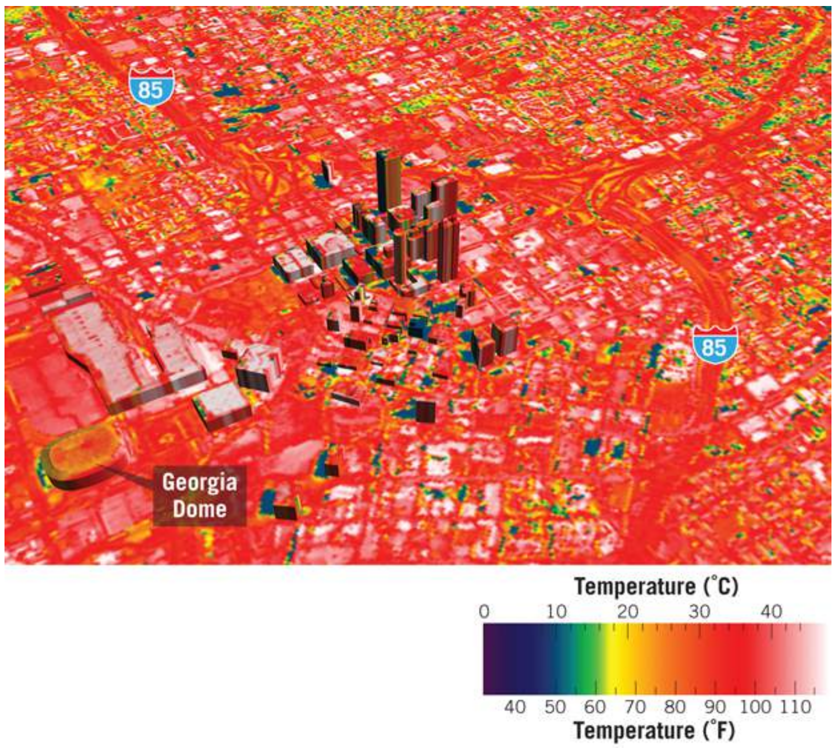
Concrete and asphalt contribute to the urban heat island effect.

A portion of the urban temperature rise is also attributable to waste heat from sources such as home heating and air conditioning, power plants, factories and other industry, and vehicles. In addition, the “blanket” of pollutants over a city contributes to a heat island by absorbing a portion of the upward-directed longwave radiation emitted by the surface and re-emitting some of this energy back to the ground.

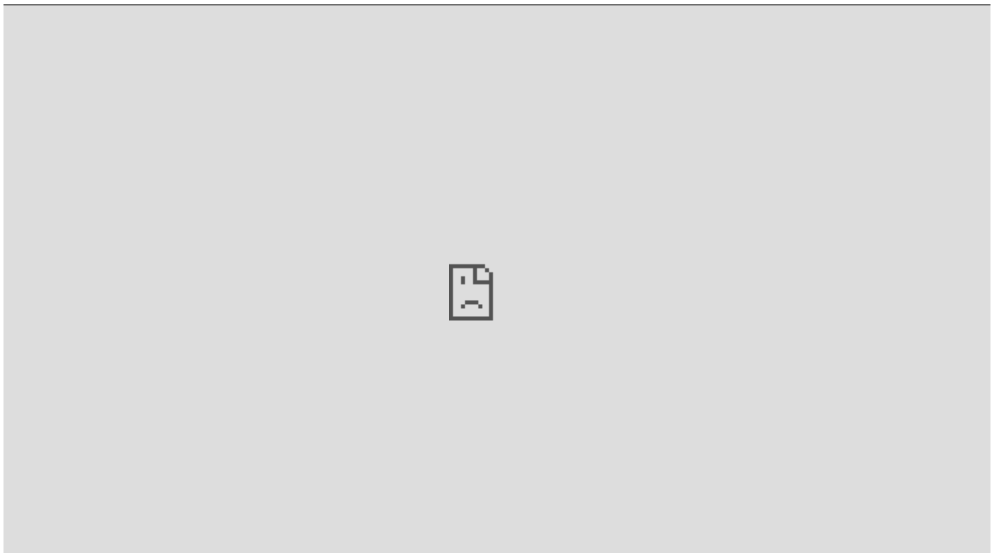
Figure 3.C is an image of central Atlanta, Georgia’s largest city, produced by collecting temperature data using a specially outfitted airplane and plotting that data on a satellite image. This map shows surface daytime temperatures, using white and red to indicate the highest temperatures and blue and green to depict cooler temperatures. Notice how the roadways and buildings in the downtown area are hot (red and white in color), while some of the areas along the upper right side of the map, which contain some residential areas, are cooler. Also notice that downtown tall buildings cast shadows across the pavement and walls of the surrounding structures, keeping small areas cool.

Figure 3.C Thermal image of Atlanta's heat island

This image was produced by collecting temperature data and plotting that data on a satellite image. This map shows surface daytime temperatures, using white and red to indicate the highest temperatures and blue and green to depict cooler temperatures. Buildings were graphically added to the image. Notice that rooftops of several buildings are particularly hot.



Watch **Video: Urban Heat Islands**



Hundreds of high-temperature records have been broken in cities across the United States in the last decade. Not only are most cities heating up more rapidly than the planet—they tend to heat up at double the rate. Even when the air temperature is 30°C (86°F), the surface temperature of an asphalt parking lot can exceed 50°C (122°F). High temperatures raise some significant public health issues and can even be deadly to at-risk segments of the population.

It should be noted, however, that cities located in arid regions, such as the U.S. Southwest, are found to have only slightly warmer temperatures than surrounding areas and are sometimes even slightly cooler. In arid regions with little vegetation, such as Las Vegas, the irrigation of lawns and planting of trees can offset some of the effects of urban heating associated with the construction of roadways and other structures. By contrast, cities built in once-forested areas, such as Atlanta, have seen a much greater heat island effect because heavily vegetated land was largely replaced by concrete and asphalt.

Apply What You Know

1. List three factors that contribute to the development of urban heat islands.

A related factor, the amount of water vapor in the air, influences daily temperature range because it is one of the atmosphere's important heat-absorbing gases. When the air is dry and the sky is clear, surface heat readily escapes at night, and the temperature can fall rapidly. By contrast, when the air is humid, absorption of outgoing longwave radiation by water vapor slows nighttime cooling.

> Dry conditions are associated with higher daily temperature ranges, mainly because of greater nighttime cooling.

Atmospheric circulation patterns strongly influence the movement of warm and cold air across a region, which directly affects temperatures. These large-scale circulation patterns are also associated with weather systems that bring cloud cover and precipitation, which reduce incoming solar radiation and result in cooler temperatures. These important influences of temperature will be considered in the following chapters.

Concept Checks 3.3

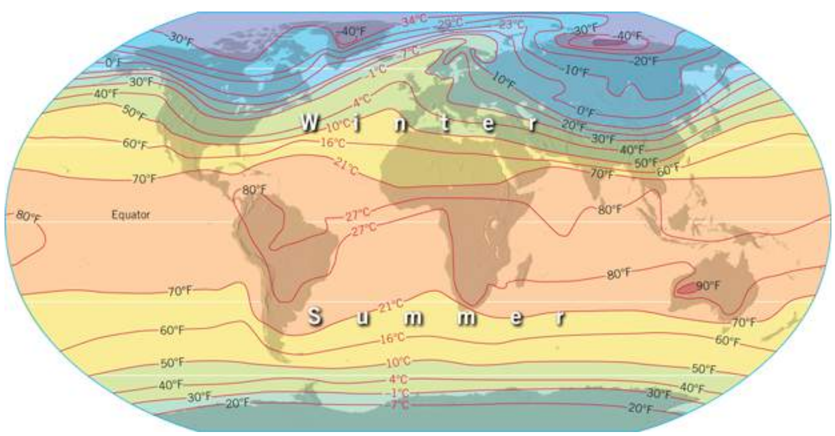
- List and briefly describe the major temperature controls.
- List four reasons why water bodies heat up and cool down slower than land surfaces.
- Describe the role that prevailing winds play in influencing temperature.
- Contrast the daily temperature range on an overcast day with that on a clear sunny day.

3.4 Global Distribution of Temperature

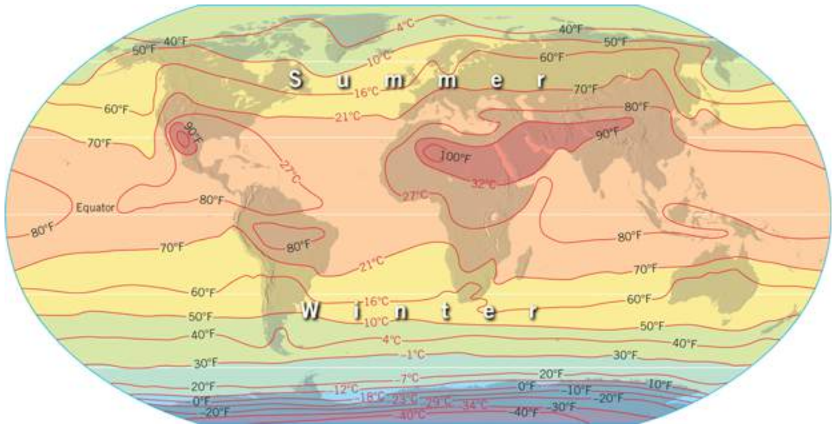
LO 4 Interpret the patterns depicted on world temperature maps.

Take a minute to study the two world maps in Figures 3.18 and 3.19. From warm colors near the equator to cool colors toward the poles, these maps portray *sea-level temperatures* in the seasonally extreme months of January and July. On these maps, you can study global temperature patterns and the effects of the controls of temperature, especially latitude, the distribution of land and water, and ocean currents.

Figure 3.18 World mean sea-level temperatures in January, in Fahrenheit (°F)



Smartfigure 3.19 **World mean sea-level temperatures in July, in Fahrenheit (°F)**



Watch **SmartFigure: January vs. July**

On both maps, the isotherms generally trend east and west and show a decrease in temperatures poleward from the tropics. This illustrates one of the most fundamental aspects of world temperature distribution: The amount of incoming solar radiation available to heat Earth's surface and the atmosphere above it is largely a function of latitude. Moreover, there is a latitudinal shifting of temperatures caused by the seasonal migration of the Sun's vertical rays. To see this, compare the color bands by latitude on the two maps.

The effect of the differential heating of land and water is clearly reflected on the January and July temperature maps—the coldest and warmest temperatures are found over land. Consequently, because temperatures do not fluctuate as much over water as over land, the north–south migration of isotherms from January to July is greater over the continents than over the oceans. In addition, the isotherms in the Southern Hemisphere, where there is less land compared to water, are much straighter than in the Northern Hemisphere, where they bend sharply northward in July and southward in January over the continents.

> The global distribution of temperatures is primarily determined by latitude and, to a lesser extent, by the distribution of land and water.

Isotherms also reveal the presence of ocean currents. The poleward transport of water warms the overlying air and results in air temperatures that are higher than would otherwise be expected for the latitude. Conversely, currents moving toward the equator produce cooler-than-expected air temperatures. Thus, warm currents cause isotherms to be deflected toward the poles, whereas cold currents cause an equatorward bending.

Figures 3.18 and 3.19 also show the seasonal extremes of temperature, and identifying the extremes enables us to see the annual range of temperature from place to place. Comparing the two maps shows that a station near the equator has a small annual range because it experiences little variation in the length of daylight and always has a relatively high Sun angle. A station in the middle latitudes, however, experiences wide variations in Sun angle and length of daylight and, hence, large variations in temperature. Therefore, we can state that the annual temperature range increases as we move from the equator toward the poles.

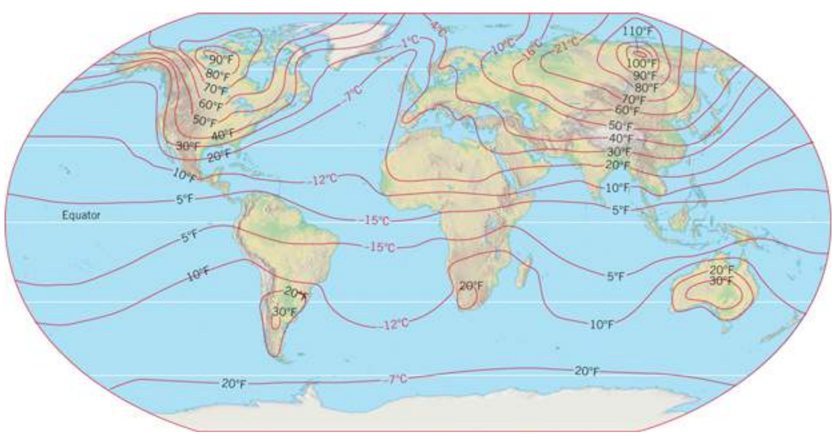
> The annual temperature range increases with an increase in latitude.

Moreover, land and water also affect seasonal temperature variations, especially outside the tropics. Continental locations must endure hotter summers and colder winters than coastal locations, where seasonal temperatures are not as extreme.

Figure 3.20, which shows the global distribution of annual temperature ranges, serves to illustrate the preceding two paragraphs. The tropics clearly experience small annual temperature variations. As expected, the highest ranges occur in the middle of large landmasses in the subpolar latitudes. It is also worth noting that annual temperature ranges in the ocean-dominated Southern Hemisphere are much smaller than in the Northern Hemisphere, with its abundance of large continents.

Figure 3.20 Global annual temperature ranges in Fahrenheit (°F)

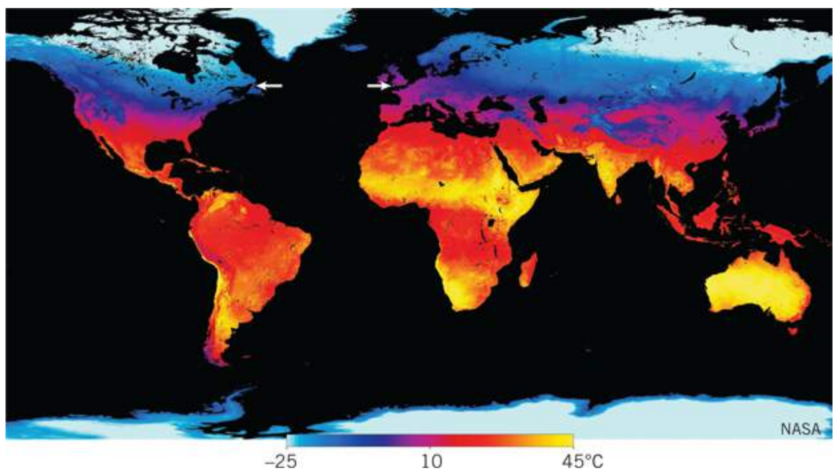
Annual ranges are small near the equator and increase toward the poles. Outside the tropics, annual temperature ranges increase as we move away from the ocean and toward the interior of large landmasses.



Watch **Video: Seasonal Changes in Land Surface Temperature**

Eye on the Atmosphere 3.2

For nearly two decades, scientists have used the Moderate Resolution Imaging Spectroradiometer (MODIS, for short) aboard NASA's *Aqua* and *Terra* satellites to gather surface temperature data from around the globe. This image shows average land-surface temperatures for the month of February over a 10-year span.



Apply What You Know

1. What are the approximate temperatures for southern Great Britain and northern Newfoundland (white arrows)?
2. Both are coastal areas at the same latitude, yet average February temperatures are quite different. Suggest a reason for this disparity.

Concept Checks 3.4

■ Why do isotherms on the January and July temperature maps generally trend east–west?

■ Refer to Figure 3.20 to determine which area on Earth experiences the highest annual temperature range. Explain why the annual range is so high.

3.5 Temperature Measurement

LO 5 Explain how different types of thermometers work and why the placement of thermometers is an important factor in obtaining accurate readings. Distinguish among Fahrenheit, Celsius, and Kelvin temperature scales.

During a typical day, many of us routinely check the current air temperature several times. Radio stations frequently report the current temperature, and the time and temperature are often placed on digital business signs. Many cars show the air temperature as part of the dashboard display. Of course, many people rely on a cellphone app to retrieve temperature information. Which of these sources are accurate and reliable?

Thermometers

A **thermometer** is an instrument that measures temperature—either mechanically or electrically (Figure 3.21). To accurately measure air temperature, a thermometer must be placed in the shade and mounted at 1.5 meters (5 feet) above the ground.

Figure 3.21 Galileo's thermoscope

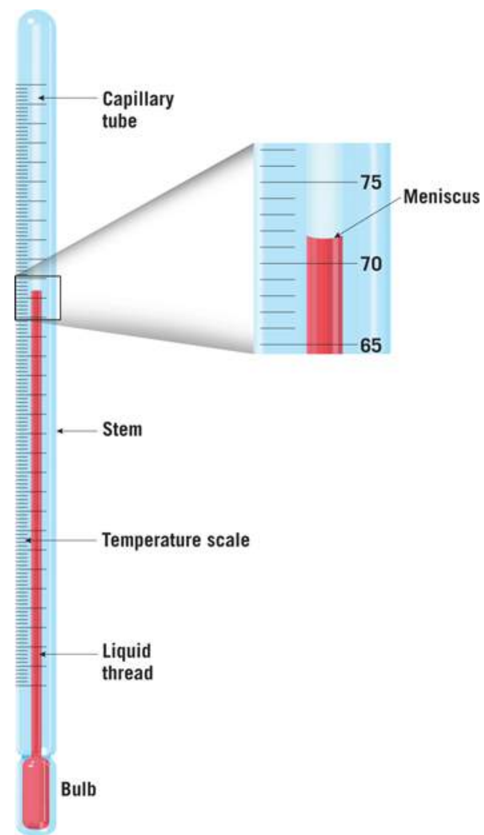
The design of this thermometer is based on an instrument called a *thermoscope* that Galileo invented in the late 1500s. Today such devices, which are fairly accurate, are used mostly for decoration. The instrument is made of a sealed glass cylinder containing a series of glass bulbs of different densities that "float" up and down as temperature causes the density of the liquid to change.

Mechanical Thermometers

Most substances expand when heated and contract when cooled, and many common thermometers operate using this property. More precisely, they rely on the fact that different substances react to temperature changes differently.

The **liquid-in-glass thermometer** shown in Figure 3.22 is a simple instrument that provides relatively accurate readings over a wide temperature range. Its design has remained essentially unchanged since it was developed in the late 1600s—consisting of a bulb containing a fluid and a stem that has been bored to form a thin capillary tube. When temperature rises, the molecules of fluid grow more active and spread out, causing the fluid to expand. Expansion of the fluid in the bulb is much greater than the expansion of the enclosing glass, forcing a thin "thread" of fluid up the capillary tube. Conversely, when temperature falls, the liquid contracts, and the thread of fluid moves back down the tube toward the bulb. The movement of the end of this thread, known as the *meniscus*, is calibrated against an established scale to indicate the temperature.

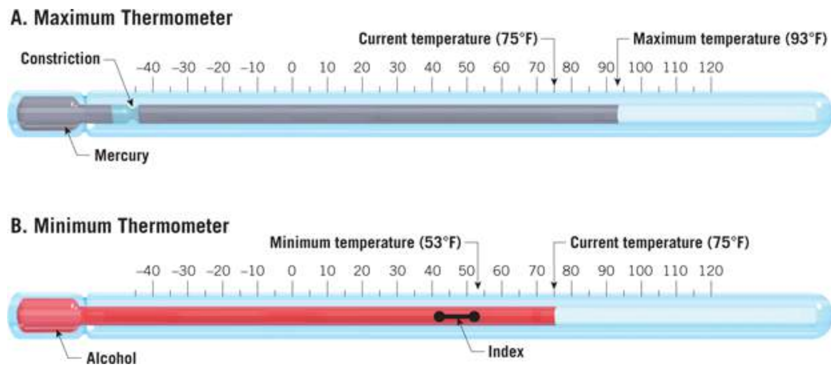
Figure 3.22 **Main components of a liquid-in-glass thermometer**



The highest and lowest daily temperatures can be measured using specially designed liquid-in-glass thermometers. Mercury is the liquid used in the **maximum thermometer**, which has a narrowed passage called a *constriction* in the bore of the glass tube, just above the bulb (Figure 3.23A). As the temperature rises, the mercury expands and is forced through the constriction. When the temperature falls, the constriction prevents the mercury from returning to the bulb. As a result, the top of the mercury column remains at the highest point (maximum temperature attained during the measurement period). The instrument is reset by shaking or whirling it to force the mercury through the constriction back into the bulb, a process that must be completed daily.

Figure 3.23 Maximum and minimum thermometers

Both examples are types of liquid-in-glass thermometers.



In contrast to a maximum thermometer that contains mercury, a **minimum thermometer** contains a liquid of low density, such as alcohol. Within the alcohol is a small dumbbell-shaped index that rests at the top of the column (Figure 3.23B). As the air temperature drops, the column shortens, and the index is pulled toward the bulb by the surface tension of the alcohol meniscus. When the temperature subsequently rises, the alcohol flows past the index, leaving it at the lowest temperature reached. To return the index to the top of the alcohol column, the thermometer is simply tilted. A minimum thermometer must be mounted horizontally; otherwise, the index will fall to the bottom.

> Mechanical thermometers rely on the fact that most substances expand when heated and contract when cooled.

Another commonly used mechanical thermometer is a **bimetal strip**. As the name indicates, this thermometer consists of two thin strips of metal that are bonded together and have widely different expansion properties. When the temperature changes, both metals expand or contract, but they do so unequally, causing the strips to curl. This change corresponds to the change in temperature. Bimetallic strips are often used in home thermostats and electrical breaker boxes.

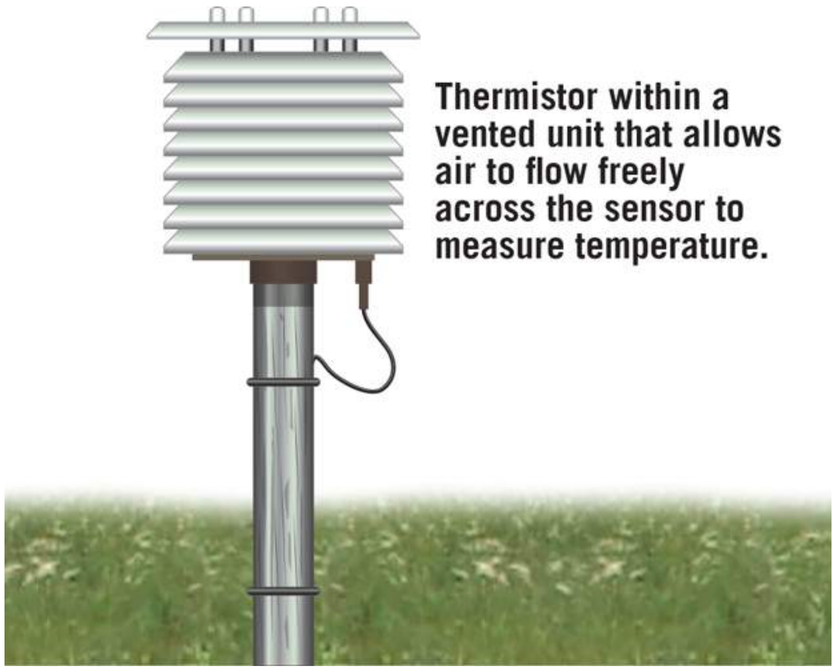
Electrical Thermometers

Modern observing stations are automated and use an electrical thermometer, called a **thermistor**, to measure temperature. A thermistor works on the concept that the flow of electricity through a metallic oxide disk or bead, called a *resistor*, is temperature dependent. As the temperature of the resistor changes, it alters the flow of electricity in a predictable way. Thus, an electric thermometer measures the flow of electricity and calibrates and displays that data as degrees of temperature. One advantage of an electric thermometer is that it provides an instant reading in any temperature scale. Thermistors, also called *digital thermometers*, are used in the medical field to measure temperature, as well as to measure the oil temperature in your vehicle.

> Thermistors are rapid-response instruments that quickly measure temperature changes.

Thermistors are used in radiosondes, where rapid temperature changes are often encountered. The National Weather Service also uses thermistors for ground-level readings. A sensor is mounted inside a shield made of louvered plastic rings, and a digital readout is placed indoors (Figure 3.24).

Figure 3.24 **Measuring temperature using a thermistor**



You might have wondered . . .

What is lowest temperature ever recorded at Earth's surface?

The lowest recorded temperature is –89°C (–129°F). This incredibly frigid temperature was recorded in Antarctica, at Russia's Vostok Station, on July 21, 1983.

Instrument Shelters

How accurate are thermometer readings? Accuracy depends not only on the design and quality of the instruments but also on where they are placed. Placing a thermometer in direct sunlight will give an excessively high reading because the instrument itself absorbs solar energy much more efficiently than does air. Placing a thermometer near a heat-radiating surface, such as a building or the ground, also yields inaccurate readings. False readings will also be recorded if air is prevented from moving freely around the thermometer.

> An instrument shelter shields instruments from direct sunshine, heat from nearby objects, and precipitation.

The ideal location is an **instrument shelter** (Figure 3.25). An instrument shelter is a white box with louvered sides to permit the free movement of air through it, while shielding the instruments from direct sunlight, heat from nearby objects, and precipitation.

Figure 3.25 Standard instrument shelter

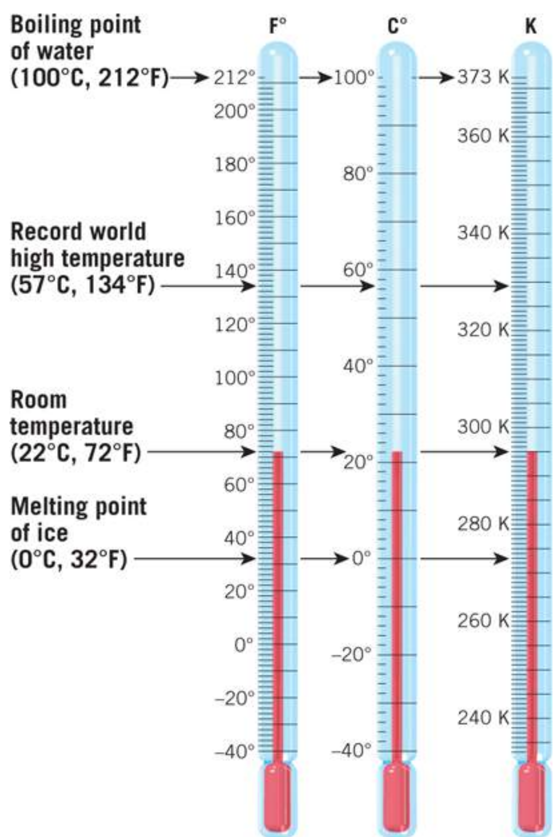
This traditional shelter is white (for high albedo) and louvered (for ventilation). It protects instruments from direct sunlight and allows for the free flow of air.

Furthermore, the shelter is placed over grass whenever possible and as far away from buildings as circumstances permit. Finally, the shelter must conform to a standardized height so that the thermometers are mounted at 1.5 meters (5 feet) above the ground.

Temperature Scales

In the United States, standard temperature information is provided in degrees Fahrenheit, which we have shown in figures throughout this chapter. However, meteorologists and geoscientists, as well as most other countries, rely on the Celsius scale. In some circumstances, scientists also use the Kelvin, or absolute, scale. Figure 3.26 compares the three commonly used temperature scales.

Figure 3.26 Three temperature scales compared



Fahrenheit Scale

In 1714, Daniel Fahrenheit, a German physicist, devised the **Fahrenheit scale**. Like all temperature scales, the Fahrenheit scale is based on reference points, although the original reference points chosen by Fahrenheit were later modified. Today, the Fahrenheit scale is defined by two fixed points, the temperature at which ice melts (32°F) and the boiling point of water (212°F). The difference between the two fixed points on the Fahrenheit scale is 180 degrees.

Celsius Scale

In 1742, 28 years after Fahrenheit invented his scale, Anders Celsius, a Swedish astronomer, devised a decimal scale on which the melting point of ice was set at 0° and the boiling point of water at 100°.* For many years it was called the *centigrade scale*, but it is now known as the **Celsius scale** after its inventor.

Because the interval between the melting point of ice and the boiling point of water is 100 degrees on the Celsius scale and 180 degrees on the Fahrenheit scale, a Celsius degree (°C) is larger than a Fahrenheit degree (°F) by a factor of 180/100, or 1.8. Therefore allowance must be made for this difference in degree size when converting from one system to the other. Also, conversions must be adjusted because the melting point of ice on the Celsius scale is at 0° rather than at 32°. This relationship is shown graphically in Figure 3.26.

The Celsius–Fahrenheit relationship is shown by the following formulas:

$$^{\circ}\mathrm{F} = (1.8 \times {}^{\circ}\mathrm{C}) + 32$$

and:

$$^{\circ}\mathrm{C} = \frac{^{\circ}\mathrm{F} - 32}{1.8}$$

You can see that the formulas adjust for degree size with the 1.8 factor and adjust for the different 0° points by adding or subtracting 32.

Kelvin Scale

For scientific purposes, a third temperature scale is used: the **Kelvin, or absolute, scale**. On this scale, degrees Kelvin are called *Kelvins* (abbreviated K). This scale is similar to the Celsius scale because its divisions are exactly the same; 100 degrees separate the melting point of ice and the boiling point of water. However, on the Kelvin scale, the melting point is set at 273 K, and the boiling point is at 373 K (Figure 3.26). The zero point represents the temperature at which all molecular motion is presumed to cease (called **absolute zero**). Thus, unlike the Celsius and Fahrenheit scales, there is no negative value on the Kelvin scale, for there is no temperature lower than absolute zero.

You might have wondered . . .

Which countries use the Fahrenheit scale?

The United States and Belize (a small country in Central America) are the only two countries that continue to use the Fahrenheit scale for everyday applications, whereas other countries employ the Celsius scale. The scientific community uses the Celsius and Kelvin scales.

Concept Checks 3.5

- ■ Describe how each of the following thermometers work: liquid-in-glass, maximum, minimum, bimetal strip, and thermistor.
- ■ In addition to using an accurate thermometer, which other factors must be considered to obtain a reliable air temperature reading?
- ■ What are the values of the melting and boiling points of water on each of the three temperature scales presented here?

* The boiling point referred to in the Celsius and Fahrenheit scales pertains to pure water at standard sea-level pressure.

3.6 Applying Temperature Data

LO 6 Summarize several applications of temperature data.

There are many useful and practical applications for temperature data. In this section you will learn about important indices that relate to energy use, agriculture, and human comfort. Because the National Weather Service and the U.S. news media still compute and report these temperature variables in Fahrenheit, we will use that scale throughout this discussion.

Degree Days

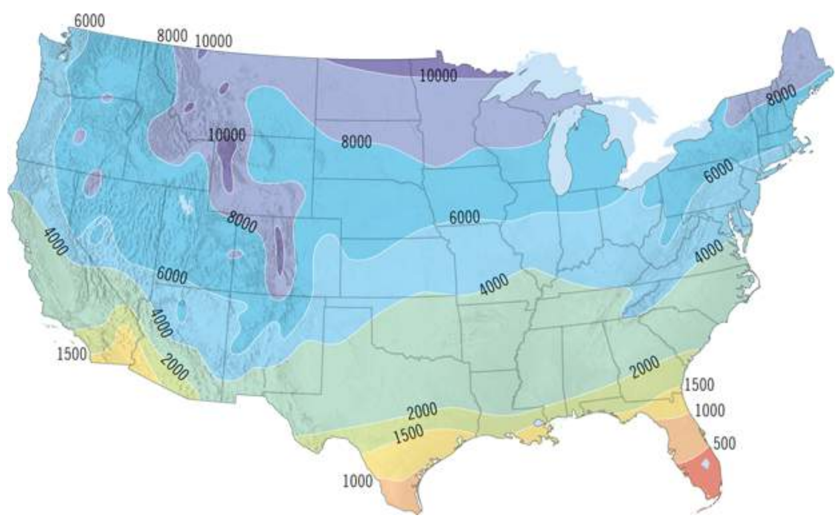
Three indices have the term *degree days* as part of their name: heating degree days, cooling degree days, and growing degree days.

Heating Degree Days

A commonly used method for evaluating energy demand is **heating degree days**. This index starts from the assumption that heating is not required in a building when the daily mean temperature outdoors is 65°F or higher. Simply, each degree of mean temperature below 65°F is counted as 1 heating degree day. Therefore, heating degree days are determined each day by subtracting the daily mean below 65°F from 65°F. Thus, a day with a mean temperature of 50°F has 15 heating degree days, and a day with an average temperature of 65°F or higher has none.

Fuel consumption for a location can be estimated by calculating the total number of heating degrees for an entire year. Figure 3.27 shows the average number of heating degree days for locations throughout the lower 48 states. The amount of fuel required to maintain a certain temperature in a building is proportional to the total heating degree days. This means that doubling the heating degree days usually doubles the fuel consumption; thus, a month with 1000 heating degree days will require twice as much fuel as for a month with 500.

Figure 3.27 **Average annual U.S. total heating degree days**



When seasonal totals are compared for different places, we can estimate differences in seasonal fuel consumption (Table 3.2). For example, more than five times as much fuel is required to heat a building in Chicago (nearly 6500 total heating degree days) than to heat a similar building in Los Angeles (almost 1300 heating degree days).

Table 3.2 Average Annual Heating and Cooling Degree Days for Selected Cities

City	Heating Degree Days	Cooling Degree Days
Anchorage, AK	10,470	3
Baltimore, MD	3807	1774
Boston, MA	5630	777
Chicago, IL	6498	830
Denver, CO	6128	695
Detroit, MI	6422	736
Great Falls, MT	7828	288
International Falls, MN	10,269	233
Las Vegas, NV	2239	3214
Los Angeles, CA	1274	679
Miami, FL	149	4361
New York City, NY	4754	1151
Phoenix. AZ	1125	4189
San Antonio, TX	1573	3038
Seattle, WA	4797	173

Source: NOAA, National Climatic Data Center.

> Heating and cooling degree days are calculations used to determine energy demand.

Cooling Degree Days

Just as fuel needs for heating can be estimated and compared by using heating degree days, the amount of power required to cool a building can be estimated by using a similar index called **cooling degree days**. Because the 65°F base temperature is also used in calculating this index, cooling degree days are determined each day by subtracting 65°F from the daily mean. Thus, if the mean temperature for a given day is 80°F, 15 cooling degree days would be accumulated. Mean annual totals of cooling degree days for selected cities are shown in Table 3.2. By comparing the totals for Baltimore and Miami, we can see that the fuel requirements for cooling a building in Miami are almost 2½ times as great as for a similar building in Baltimore.

Growing Degree Days

Another practical application of temperature data is used in agriculture to determine the approximate date when crops will be ready for harvest. This simple index is called **growing degree days**. The number of growing degree days for a particular crop on any day is the difference between the daily mean temperature and the base temperature of the crop, which is the minimum temperature required for it to grow. For example, the base temperature for growing sweet corn is 50°F, and for peas is 40°F. Thus, on a day when the mean temperature is 75°F, the number of growing degree days for sweet corn is 25, and the number for peas is 35.

> Growing degree days are used to estimate crop maturity.

Starting with the onset of the growth season, the daily growing degree-day values are added. Thus, if 2000 growing degree days are needed for a crop to mature, it should be ready to harvest when the accumulation reaches 2000. Although many factors important to plant growth are not included in the index, such as moisture conditions and sunlight, this system nevertheless serves as a simple and widely used tool to determine approximate dates of crop maturity.

Indices of Human Discomfort

Summertime weather reports sometimes include the potential harmful effects of high temperatures coupled with high humidity (see Severe & Hazardous Weather Box 3.3). By contrast, in winter when temperatures are low, we are reminded of the effect of strong winds. In the first instance, we are cautioned about heat stress and the possibility of heat stroke, and in the second case we are warned about windchill and the potential dangers of frostbite. These indices are expressions of **apparent temperature**—the perceived increase or decrease in temperature felt by the human body.

Severe & Hazardous Weather 3.3

Heat Waves

A *heat wave* is a prolonged period of abnormally hot and usually humid weather that typically lasts from a few days to several weeks. The impact of heat waves on individuals varies greatly, but it can be serious and even deadly. Elderly people are the most vulnerable because heat puts more stress on weak hearts and bodies. People who live in poverty and often cannot afford air conditioning also suffer disproportionately. Studies also show that the temperature at which death rates increase varies from city to city. In Dallas, Texas, a temperature of 103°F is required before the death rate climbs, whereas in San Francisco, the demarcation is 84°F.

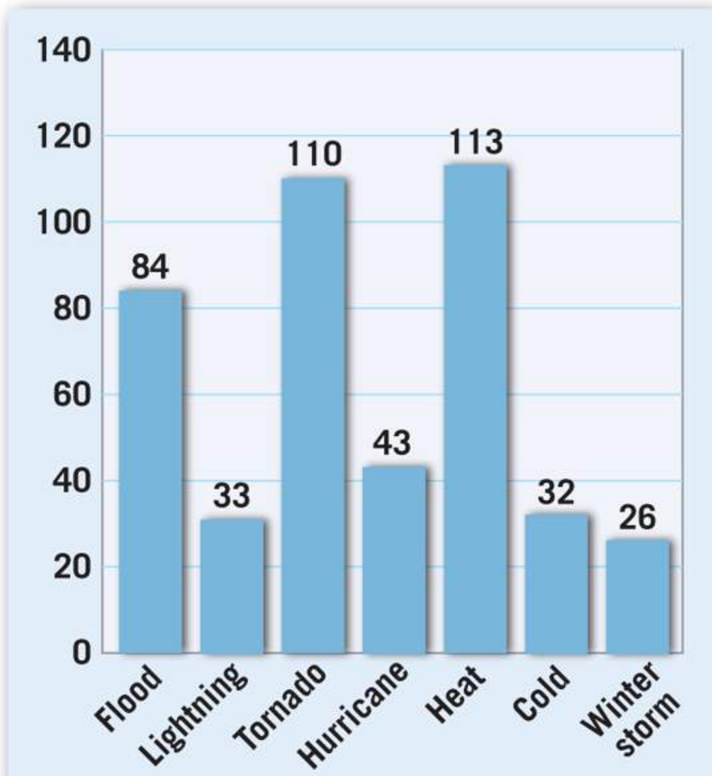
> A *heat wave* is a period of abnormally hot and usually humid weather typically lasting from a few days to several weeks.

Deadly Impacts

Why don't heat waves elicit the same sense of fear or urgency as tornadoes, hurricanes, and flash floods? One explanation is that oppressive temperatures may occur over many days before a heat wave exacts its toll, rather than causing devastation in just a few minutes or a few hours. Nevertheless, heat waves cause more deaths, on average, than any other weather-related event (Figure 3.D).

Figure 3.D Average annual U.S. weather-related fatalities for the 10-year period 2006–2015

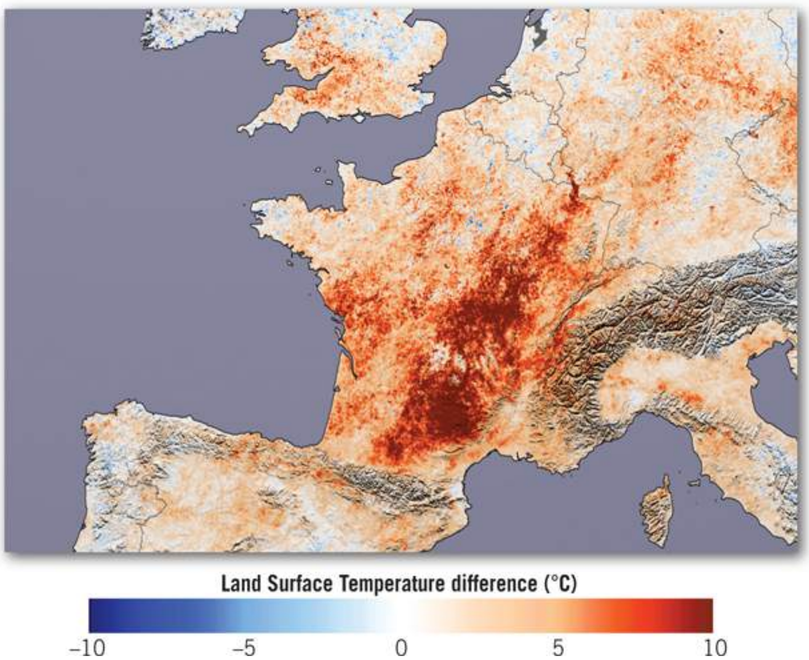
Heat is the number-one cause of weather-related fatalities.



In the summer of 2003, much of Europe experienced perhaps its worst heat wave in more than a century (Figure 3.E). Based on government records, it was estimated that nearly 35,000 people perished, with France suffering the greatest number of heat-related fatalities—about 14,000.

Figure 3.E European heat wave

This image is derived from satellite data and shows the difference in daytime land-surface temperatures during the 2003 European heat wave (July 20–August 20) as compared to the four preceding years. The zone of deep red shows where temperatures were 10°C (18°F) hotter than in the other years.



The severity of heat waves is usually greatest in cities because of the *urban heat island* (see Box 3.2). Large cities do not cool off as much at night during heat waves as rural areas, which can be a critical difference in the amount of heat stress experienced in inner cities. In addition, the stagnant atmospheric conditions usually associated with heat waves trap pollutants in urban areas and add the stresses of severe air pollution to the already dangerous conditions caused by high temperatures.

> A heat wave is usually most severe in cities.

Heat Waves and Global Warming

Among the possible consequences of global warming is an increase in the frequency and severity of heat waves. A 2013 report by the Intergovernmental Panel on Climate Change states that it is very likely that human activities have contributed to observed changes in temperature extremes since the mid-twentieth century. The report also notes that as we advance through the 21st century, warmer and/or more frequent hot days and nights over most land areas are virtually certain, and it is *very likely* that heat waves will occur with a higher frequency and have longer durations.

Weather Safety

According to the National Weather Service, heat-related deaths are preventable if you follow a few safety rules:

- Limit strenuous outdoor activities when extreme heat is forecast.
- Stay hydrated by drinking plenty of fluids.
- Check on the elderly and people without air conditioning.
- If you must be outside, stay hydrated and take breaks in the shade as often as possible.

Apply What You Know

1. How do the number of fatalities related to heat waves compare to the number of deaths caused by other weather phenomena?
2. Why are heat waves worse in cities?

Watch **Video: Temperatures and Agriculture**

The human body is a heat generator that continually releases energy. Anything that influences the rate of heat loss from the body also influences our sensation of temperature, thereby affecting our feeling of comfort. Several factors determine the thermal comfort of the human body, and temperature and humidity are two primary factors.

Heat Stress

Why are hot, muggy days so uncomfortable? Humans, like other mammals, are warm-blooded creatures who maintain a constant body temperature regardless of the temperature of the environment. The main way our bodies prevent overheating is by perspiring. However, this process does little to cool the body unless the perspiration evaporates (the cooling created by the evaporation of perspiration reduces body temperature). Because high humidity impedes evaporation, people are generally more uncomfortable on hot, humid days than on hot, dry days.

One index widely used by the National Weather Service is the **heat stress index**, or simply the *heat index*, which combines temperature and humidity to establish the degree of comfort or discomfort.

> The heat stress index is the perceived increase in temperature felt by the body as a result of humidity.

Examine Figure 3.28, which illustrates that as relative humidity increases, the apparent temperature, and heat stress, increases as well. It is important to note that factors such as the length of exposure to direct sunlight, wind speed, and general health of the individual greatly affect the amount of stress a person will experience. In addition, while a period of hot, humid weather in New Orleans might be reasonably well tolerated by its residents, a similar event in a northern city such as Minneapolis could be dangerous. This is because such weather is more taxing on people who live where these conditions are relatively rare compared to those who are acclimated to living in areas having prolonged periods of heat and high humidity.

Figure 3.28 **Heat index expresses apparent temperature**

As relative humidity increases, apparent temperature increases as well. For example, if the air temperature is 90°F and the relative humidity is 65 percent, it would "feel like" 103°F.

Heat Index

Air Temperature (°F)	Relative Humidity (%) 40	45	50	55	60	65	70	75	80	85	90	95	100
110	136												
108	130	137											
106	124	130	137										
104	119	124	131	137									
102	114	119	124	130	137								
100	109	114	118	124	129	136							
98	105	109	113	117	123	128	134						
96	101	104	108	112	116	121	126	132					
94	97	100	102	106	110	114	119	124	129	135			
92	94	96	99	101	105	108	112	116	121	126	131		
90	91	93	95	97	100	103	106	109	113	117	122	127	132
88	88	89	91	93	95	98	100	103	106	110	113	117	121
86	85	87	88	89	91	93	95	97	100	102	105	108	112
84	83	84	85	86	88	89	90	92	94	96	98	100	103
82	81	82	83	84	84	85	86	88	89	90	91	93	95
80	80	80	81	81	82	82	83	84	84	85	86	86	87

With prolonged exposure and/or physical activity
Extreme danger Heat stroke or sunstroke highly likely
Danger Sunstroke, muscle cramps, and/or heat exhaustion likely
Extreme caution Sunstroke, muscle cramps, and/or heat exhaustion possible
Caution Fatigue possible

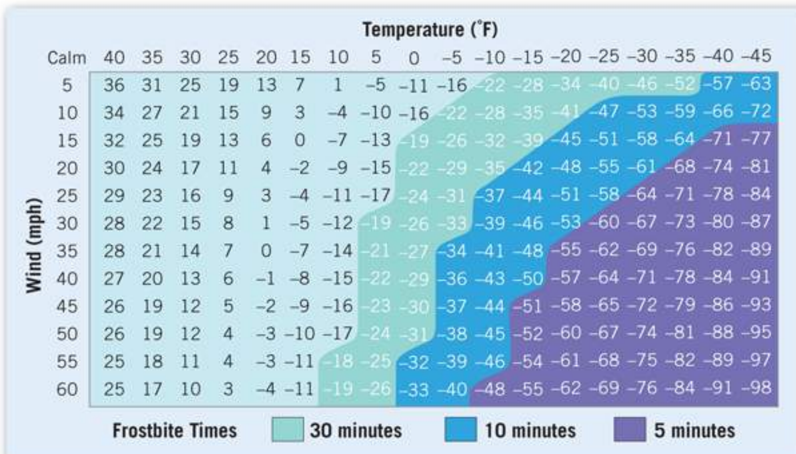
Windchill

When the wind blows on a cold day, we realize that we would be more comfortable if the wind would stop. A stiff breeze penetrates ordinary clothing and reduces the body's capacity to retain heat while causing exposed parts of the body to chill rapidly. Not only is cooling by evaporation heightened in this situation, but the wind also acts to carry heat away from the body by constantly replacing warmer air next to the body with colder air. Thus, *windchill* is the perceived decrease in air temperature felt by the body due to the flow of air.

The U.S. National Weather Service and the Meteorological Services of Canada use the **windchill temperature index**, which is designed to calculate how the wind and cold feel on human skin (Figure 3.29). The index accounts for wind effects at face level and takes into account body heat-loss estimates. It was tested and refined by exposing human subjects to a chilled wind tunnel. The windchill chart includes a frostbite indicator, which shows where temperature, wind speed, and exposure time produce frostbite (Figure 3.29).

Figure 3.29 Windchill chart

The shaded areas on the chart indicate frostbite danger. Each shaded zone shows how long a person can be exposed before frostbite develops. For example, a temperature of 0°F and a wind speed of 15 miles per hour will produce a windchill temperature of –19°F. Under these conditions, exposed skin can freeze in 30 minutes.



Temperature (°F)

Wind (mph) / Calm	40	35	30	25	20	15	10	5	0	–5	–10	–15	–20	–25	–30	–35	–40	–45
5	36	31	25	19	13	7	1	–5	–11	–16	–22	–28	–34	–40	–46	–52	–57	–63
10	34	27	21	15	9	3	–4	–10	–16	–22	–28	–35	–41	–47	–53	–59	–66	–72
15	32	25	19	13	6	0	–7	–13	–19	–26	–32	–39	–45	–51	–58	–64	–71	–77
20	30	24	17	11	4	–2	–9	–15	–22	–29	–35	–42	–48	–55	–61	–68	–74	–81
25	29	23	16	9	3	–4	–11	–17	–24	–31	–37	–44	–51	–58	–64	–71	–78	–84
30	28	22	15	8	1	–5	–12	–19	–26	–33	–39	–46	–53	–60	–67	–73	–80	–87
35	28	21	14	7	0	–7	–14	–21	–27	–34	–41	–48	–55	–62	–69	–76	–82	–89
40	27	20	13	6	–1	–8	–15	–22	–29	–36	–43	–50	–57	–64	–71	–78	–84	–91
45	26	19	12	5	–2	–9	–16	–23	–30	–37	–44	–51	–58	–65	–72	–79	–86	–93
50	26	19	12	4	–3	–10	–17	–24	–31	–38	–45	–52	–60	–67	–74	–81	–88	–95
55	25	18	11	4	–3	–11	–18	–25	–32	–39	–46	–54	–61	–68	–75	–82	–89	–97
60	25	17	10	3	–4	–11	–19	–26	–33	–40	–48	–55	–62	–69	–76	–84	–91	–98

Frostbite Times: 30 minutes; 10 minutes; 5 minutes

> Windchill is the perceived decrease in air temperature felt by the body as a result of the flow of air.

It is worth noting that the windchill temperature is only an estimate of human discomfort. The degree of discomfort felt by different people varies because it is influenced by many factors. Even if clothing is assumed to be the same, individuals vary widely in their responses because of such factors as age, physical condition, state of health, and level of activity. Nevertheless, as a relative measure, the windchill temperature index is useful because it allows people to make more informed judgments regarding the potential harmful effects of wind and cold.

Concept Checks 3.6

■ Distinguish among heating, cooling, and growing degree days.

■ Why does high humidity contribute to summertime discomfort?

■ Explain why strong winds make temperatures in winter feel lower than the thermometer reading.

Concepts in Review

3.1 For the Record: Air-Temperature Data

LO 1 Calculate five commonly used types of temperature data and interpret a map that depicts temperature data using isotherms.

Key Terms

daily mean temperature

daily temperature range

monthly mean temperature

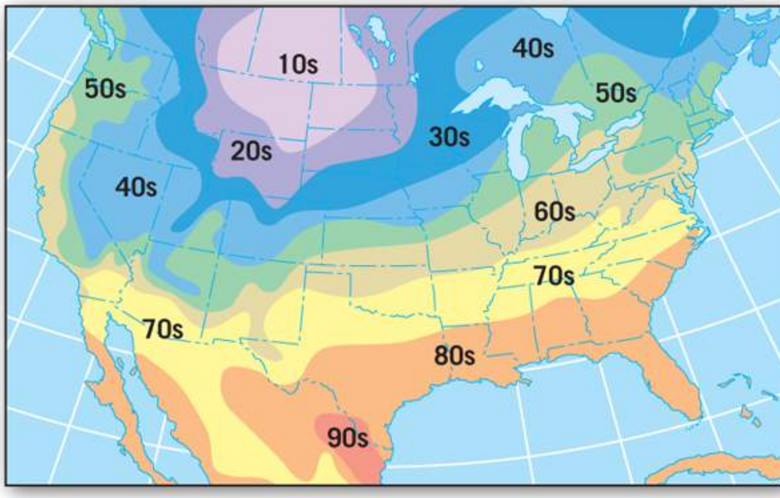
annual mean temperature

annual temperature range

isotherm

temperature gradient

- Common temperature data include daily mean temperature, daily temperature range, monthly mean temperature, annual mean temperature, and annual temperature range.
- Temperature distribution is often shown on a map by using isotherms, which are lines of equal temperature. The spacing of the isotherms determines the temperature gradient. Closely spaced isotherms indicate a rapid rate of temperature change and a large or steep temperature gradient.



10s
40s
50s
50s
20s
30s
40s
60s
70s
70s
80s
90s

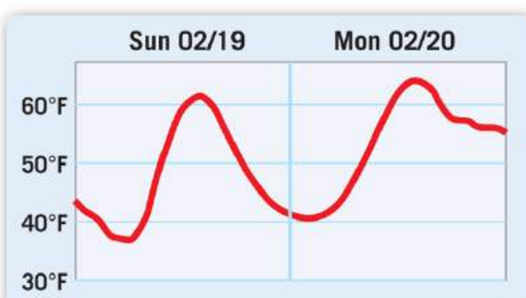
3.2 Cycles of Air Temperature

LO 2 Discuss the basic daily and annual cycles of air temperature.

Key Term

meteogram

- The main control of the daily cycle of air temperature is Earth's rotation, which causes a place to move into and out of daylight. The time of highest temperature usually does not coincide with the time of maximum intensity of solar radiation.
- The seasonal temperature cycle is more pronounced the further you get from the equator.
- As a result of the mechanism by which Earth's atmosphere is heated, the highest and lowest mean temperatures usually do not coincide with the periods of maximum and minimum incoming solar radiation.



3.3 Why Temperatures Vary

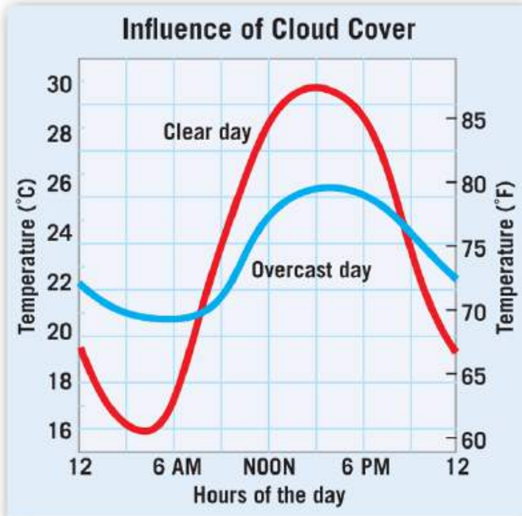
LO 3 Name the principal controls of temperature and use examples to describe their effects.

Key Terms

temperature control

specific heat

- Controls of temperature are factors that cause temperature to vary at a given location. The primary control of temperature is *latitude* because it determines the annual variations in Sun angle and length of daylight.
- Altitude is an easily visualized control: The higher up you go in elevation, the colder it gets; therefore, mountains are cooler than adjacent lowlands.
- Land and water heat and cool differently. Land areas experience greater temperature extremes than water-dominated areas.
- Poleward-moving warm ocean currents moderate winter temperatures, while equatorward movement of cold currents moderate summer temperatures.
- The effect of cloud cover is to reduce the daily temperature range by lowering the daytime maximum and raising the night-time minimum.
- Geographic position also affects temperature; for example, mountains act as barriers to marine influence, and windward coastal locations tend to experience cooler summers and milder winters than leeward coastal locations. Also, the windward (upslope) side of a mountain tends to be cooler, while the leeward (downslope) side tends to be warmer.

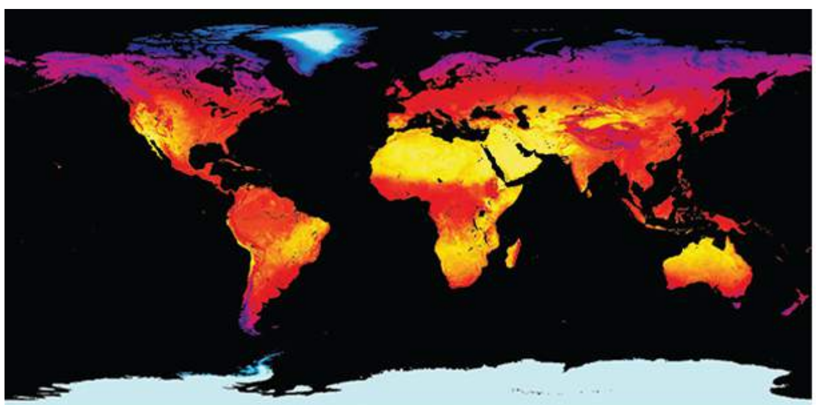


Influence of Cloud Cover
30
28
26
24
22
20
18
16
Temperature (°C)
Clear day
Overcast day
85
80
75
70
65
60
Temperature (°F)
12
6 AM
NOON
6 PM
12
Hours of the day

3.4 Global Distribution of Temperature

LO 4 Interpret the patterns depicted on world temperature maps.

- On world maps showing January and July mean temperatures, isotherms generally trend east–west and show a decrease in temperature moving from the tropics toward the poles. When the two maps are compared, a seasonal latitudinal shift of temperatures is easily seen.
- Bending isotherms often reveal the locations of ocean currents.
- Annual temperature range is small near the equator and increases with an increase in latitude. Outside the tropics, annual temperature range also increases as marine influence diminishes.



NASA

3.5 Temperature Measurement

LO 5 Explain how different types of thermometers work and why the placement of thermometers is an important factor in obtaining accurate readings. Distinguish among Fahrenheit, Celsius, and Kelvin temperature scales.

Key Terms

thermometer

liquid-in-glass thermometer

maximum thermometer

minimum thermometer

bimetal strip

thermistor

instrument shelter

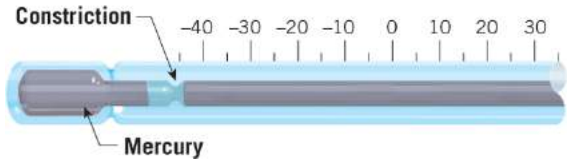
Fahrenheit scale

Celsius scale

Kelvin (absolute) scale

absolute zero

- Thermometers measure temperature either mechanically or electrically. Most mechanical thermometers are based on the property that a material expands when heated and contracts when cooled.
- Electrical thermometers, called thermistors, use resistors that measure the rate of flow of an electrical current to measure temperature.
- To obtain an accurate air temperature, the best place to locate a thermometer is in a properly situated instrument shelter.
- Three common scales are the Fahrenheit scale, Celsius scale, and Kelvin, or absolute, scale.


Constriction
−40 −30 −20 −10 0 10 20 30
Mercury

3.6 Applying Temperature Data

LO 6 Summarize several applications of temperature data.

Key Terms

heating degree days

cooling degree days

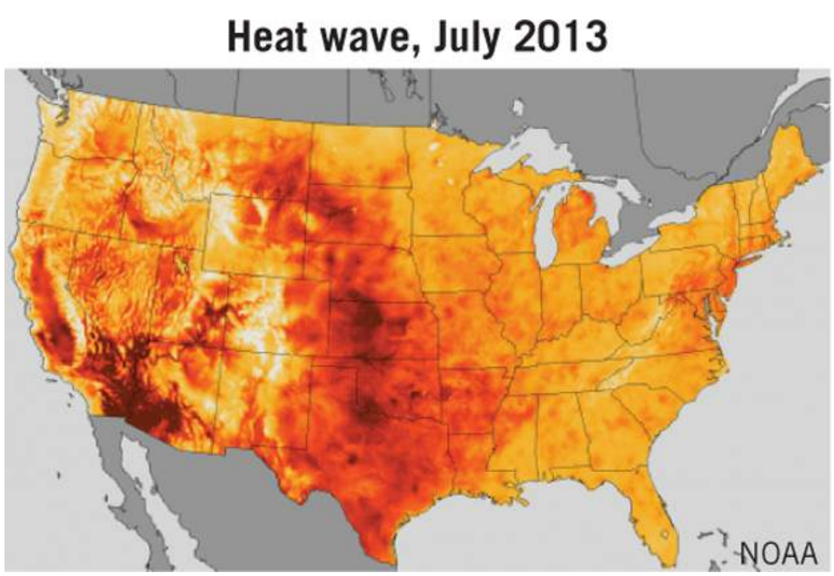
growing degree days

apparent temperature

heat stress index

windchill temperature index

- Heating and cooling degree days are calculations used to evaluate energy demand.
- Growing degree days are used to determine the approximate date when crops will be ready to harvest.
- Heat stress and windchill indices are uses of temperature data that relate to apparent temperature—the temperature people perceive.



Exercises and Online Activities

Mastering Meteorology™

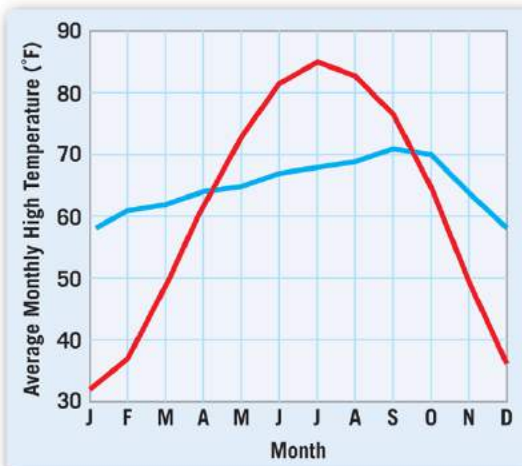
For instructor-assigned homework, test prep resources, and other learning materials, visit **Mastering Meteorology.**

Review Questions

1. Describe each of the following measures: monthly mean temperature, annual mean temperature, and annual temperature range.
2. What information does an isotherm tell us?
3. What is meant by a steep temperature gradient?
4. Describe how temperature typically changes throughout the day. When is the warmest part of the day? When is the coldest part of the day? Why?
5. What is the most important control of temperature at a given location?
6. How do large bodies of water affect local temperatures?
7. What role do ocean currents play in determining local temperatures?
8. Describe the effect that altitude has on temperature.
9. Give an example of how geographic position and prevailing winds influence local temperatures.
10. Briefly explain the role that clouds play in controlling daily temperatures.
11. Are clear nights warmer or colder than cloudy nights? Clear days?
12. Explain why the isotherms on a world mean temperature map like Figure 3.18 run nearly east to west. Are isotherms more likely to turn north and south over land or over water, and why?
13. How does a liquid-in-glass thermometer work?
14. Describe how a thermistor works.
15. Briefly describe apparent temperature.
16. What is a heating degree day? Cooling degree day? Growing degree day?
17. Define *windchill*.
18. What is the heat stress index, and what factors determine a heat index value?

Give It Some Thought

1. If you were asked to identify the coldest city in the United States, what statistics could you use? List at least three different ways of selecting the coldest city.
2. The accompanying graph shows monthly high temperatures for Urbana, Illinois, and San Francisco, California. Although both cities are located at about the same latitude, the temperatures they experience are quite different. Which line on the graph represents Urbana, and which represents San Francisco? How did you figure this out?



3. Determine how each of the following factors will influence daily temperatures and the annual temperature cycle. Your answer choices for each blank are: *increase, decrease* or *not change*.
   - **a.** If you move from a high latitude location to a location near the equator,
     the daily mean temperature in the summer will ____;
     the daily mean temperature in the winter will ____; and
     the annual temperature range will ____.
   - **b.** If you move from the west coast to a location on the east coast of the United States,

the daily mean temperature in the summer will ____;

the daily mean temperature in the winter will ____; and

the annual temperature range will ____.

c. If you move from sea level to a location a mile above sea level,

the daily mean temperature in the summer will ____;

the daily mean temperature in the winter will ____; and

the annual temperature range will ____.

4. On which summer day, from the choices below, would you expect the greatest temperature range? Which would have the smallest range in temperature? Explain your choices.

a. Cloudy skies during the day and clear skies at night

b. Clear skies during the day and cloudy skies at night

c. Clear skies during the day and clear skies at night

d. Cloudy skies during the day and cloudy skies at night

5. The accompanying scene shows an island near the equator in the Indian Ocean. Describe how latitude, altitude, and the differential heating of land and water influence the climate of this place.

6. The accompanying sketch map represents a hypothetical continent in the Northern Hemisphere. One isotherm has been placed on the map.

- **a.** Is the temperature higher at city A or city B? Explain.
- **b.** Is the season winter or summer? How are you able to determine this?
- **c.** Describe (or sketch) the position of this isotherm 6 months later.

7. The data below are mean monthly temperatures in °C for an inland location that lacks any significant ocean influence. Based on the *annual temperature range*, what is the approximate latitude of this place? Are these temperatures what you would normally expect for this latitude? If not, what control would explain these temperatures?

J	F	M	A	M	J	J	A	S	O	N	D
6.1	6.6	6.6	6.6	6.6	6.1	6.1	6.1	6.1	6.1	6.6	6.6

8. Palm trees in Scotland? Yes, in the 1850s and 1860s, amateur gardeners planted palm trees on the western shore of Scotland. The latitude pictured is 57° north, about the same as the northern portion of Labrador, across the Atlantic in Canada. Surprisingly, these exotic plants flourished. Suggest a possible explanation for how these palms can survive at this latitude.

By the Numbers

1. Refer to the meteogram in Figure 3.2. Determine the maximum and minimum temperatures for each day of the week. Use these data to calculate the daily mean and daily range for each day.
2. By referring to the world maps of temperature distribution for January and July (Figures 3.18 and 3.19), determine the approximate January mean, July mean, and annual temperature range for a place located at 60° north latitude, 80° east longitude; and a place located at 60° south latitude, 80° east longitude.
3. Calculate the annual temperature range for three cities in Appendix G. Try to choose cities with different ranges and explain these differences in terms of the controls of temperature.
4. Referring to Figure 3.29, determine windchill temperatures under the following circumstances:
   - **a.** Temperature = 5°F, wind speed = 15 mph
   - **b.** Temperature = 5°F, wind speed = 30 mph
5. The mean temperature is 55°F on a particular day. The following day, the mean drops to 45°F. Calculate the number of heating degree days for each day. How much more fuel would be needed to heat a building on the second day compared with the first day?
6. Use the appropriate formulas to convert the following temperatures:

Average room temperature	72°F	_____°C	_____K
Temperature on a very hot day	_____°F	_____°C	310K
Boiling point of water	_____°F	100°C	_____K
Melting point of water	32 °F	_____°C	_____K
Lowest temperature ever recorded	_____°F	_____°C	180K
Average human body temperature	98.6°F	_____°C	_____K

Beyond the Textbook

1. Temperature versus Latitude

This activity investigates the relationship between temperature and latitude.

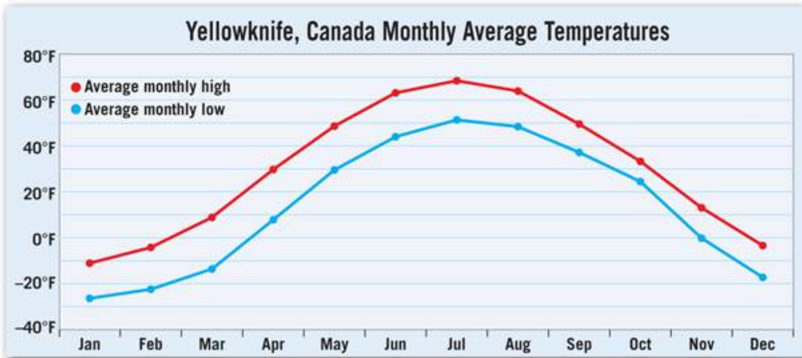
Part A. Go to usclimatedata.com and find the monthly average temperatures for your location by clicking on your state and then on a city name near you. (If you live outside the United States, do an Internet search for your location, requesting monthly average temperatures.)

1. For your location, what is the coolest month of the year? Warmest month?
2. What is the average high temperature for the coolest month? Warmest month?
3. What is the approximate difference, in degrees, between the average high monthly temperature for the coolest month and the average high monthly temperature for the warmest month?
4. What are the hours of sunshine for the coolest and warmest months?

Part B. The graph below shows the monthly average high and low temperatures for Yellowknife, Canada, located about 62° north latitude. Find comparable monthly temperature data for Peoria, Illinois (a midlatitude city located about 40° north latitude), and San Antonio, Texas (roughly 30° north latitude) using usclimatedata.com.

5. List the monthly high temperature for the warmest and coolest months of the year for Yellowknife, Canada; Peoria, Illinois; and San Antonio, Texas.
6. List the monthly low temperature for the warmest and coolest months of the year for these same locations.

7. Explain, in your own words, the relationship between temperature variations that are caused mainly by latitude.



Part C. Use usclimatedata.com to locate the graphs showing the monthly mean temperatures for Virginia Beach, Virginia, and San Francisco, California.

8. List the monthly high temperature for the warmest and coolest months of the year for each city. Then list the monthly low temperatures for the warmest and coolest months.
9. Both cities are located near the ocean and are at the same latitude (about 37°N) but have much different seasonal temperatures. Explain this difference.

2. Southern Hemisphere Weather and Climate

Part A. Search the Internet to find the monthly average temperatures for Perth, Australia, and compare them to the data you found for Peoria, Illinois, in the above exercise.

1. Which month is the warmest in Peoria? In Perth? Which month is the coolest in each city?
2. Briefly describe why the warmest and coolest months are different in Peoria than in Perth.

Part B. Search the Internet to find the latitude of your location. Then, choose a city in the Southern Hemisphere that is about the same latitude as your location. Note the geographic position of the city you selected, such as altitude or proximity to a large body of water.

3. Search the Internet to find the current weather conditions for the city you selected. How is the weather at this Southern Hemisphere city different from the weather at your location?
4. List several reasons for the differences you noted in Question 1. (*Hint*: Seasonal difference may not be the primary difference.) Continue searching the Internet to determine what other geographic factors might influence the weather at your selected city.

Chapter 4 Moisture and Atmospheric Stability

Rain showers near the Mitten Buttes, Monument Valley, Arizona.

Focus on Concepts

Each statement represents the primary learning objective for the corresponding major heading within the chapter. After you complete the chapter, you should be able to:

1. Describe the movement of water through the hydrologic cycle. List and describe water's unique properties (4.1).
2. Summarize the six processes by which water changes from one state of matter to another. For each, indicate whether energy is absorbed from or released to the environment (4.2).
3. Explain the relationship between air temperature and the amount of water vapor needed to saturate air (4.3).
4. List and describe the ways relative humidity changes in nature. Compare relative humidity to dew-point temperature (4.4).
5. Describe adiabatic temperature changes and explain why the wet adiabatic rate of cooling is less than the dry adiabatic rate (4.5).
6. Identify four mechanisms that cause air to rise (4.6).
7. Explain the relationship between environmental lapse rate and stability (4.7).
8. List the primary factors that influence the stability of air (4.8).

Water vapor is an odorless, colorless gas that mixes freely with the other gases of the atmosphere. Unlike oxygen and nitrogen—the two most abundant components of the atmosphere—water can change from one state of matter to another (solid, liquid, or gas) at the temperatures and pressures experienced on Earth. Because of this unique property, water leaves the oceans as a gas and returns to the oceans as a liquid.

4.1 Water on Earth

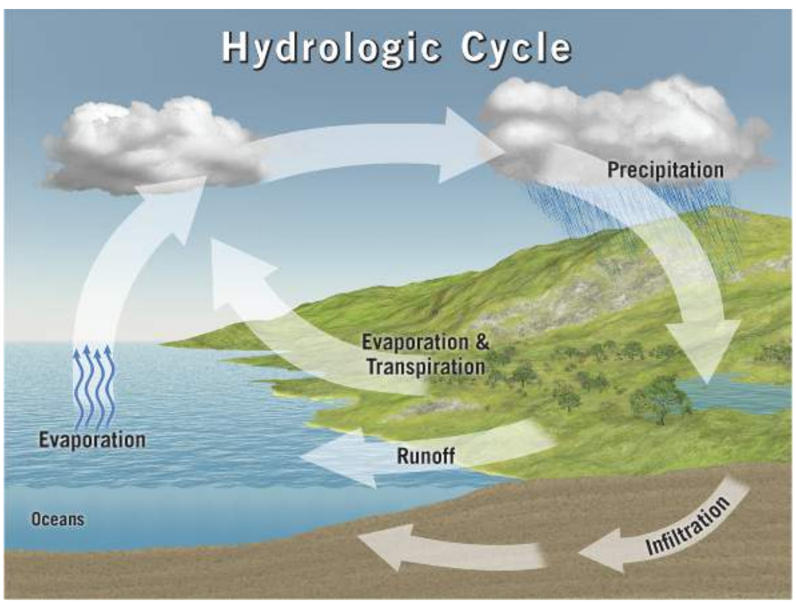
LO 1 Describe the movement of water through the hydrologic cycle. List and describe water's unique properties.

Water is found everywhere on Earth—in the oceans, glaciers, rivers, lakes, air, soil, and living tissue. The vast majority of the water on or close to Earth's surface (over 97 percent) is saltwater found in the oceans. Much of the remaining 3 percent is stored in the ice sheets of Antarctica and Greenland. Only a meager 0.001 percent is found in the atmosphere, and most of this is in the form of water vapor.

Movement of Water Through the Atmosphere

The continuous exchange of water among the oceans, the atmosphere, and the continents is called the **hydrologic cycle** (Figure 4.1). Water from the oceans and, to a lesser extent, from land areas evaporates into the atmosphere. Winds transport this moisture-laden air, often over great distances, until the process of cloud formation causes the water vapor to condense into tiny liquid cloud droplets.

Smartfigure 4.1 **Earth's hydrologic cycle**



Watch **SmartFigure: The Water Cycle**

Watch **Video: Hydrologic Cycle**

The process of cloud formation may result in precipitation. The precipitation that falls into the ocean has ended its cycle and is ready to begin another. The remaining precipitation falls over the land. A portion of the water that falls on land soaks into the ground (*infiltration*) to become groundwater. The remainder, which flows along Earth's surface, is called *runoff*.

Much of the groundwater and runoff eventually returns to the atmosphere through evaporation. A smaller amount of groundwater is taken up by plants, which release it into the atmosphere through a process called *transpiration* (or *evapotranspiration*).

The total amount of water vapor in the atmosphere remains fairly constant. Therefore, the average annual precipitation over Earth must be roughly equal to the quantity of water lost through evaporation. However, over the continents, precipitation exceeds evaporation. Evidence for the roughly balanced hydrologic cycle is found in the fact that the level of the world's oceans is not dropping.

> The hydrologic cycle is the movement of water between the oceans, the atmosphere, and the continents.

This continuous movement of water through the hydrologic cycle holds the key to the distribution of moisture over the surface of our planet and is intricately related to all atmospheric phenomena.

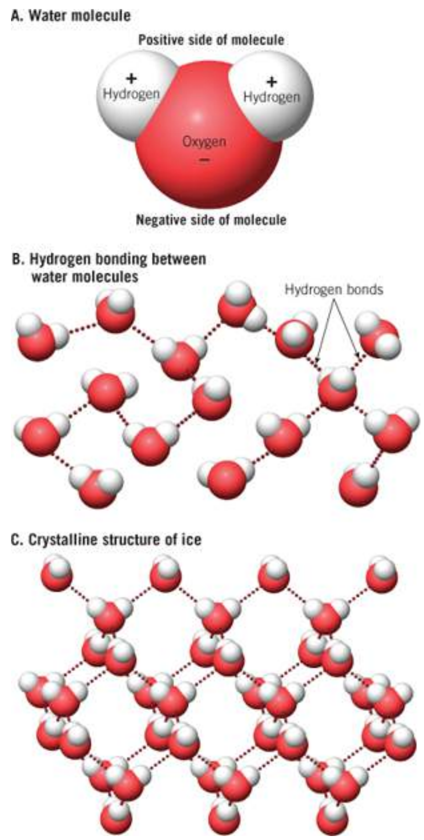
Water: A Unique Substance

Water has unique properties that set it apart from most other substances. For instance, (1) water is the only *liquid* found at Earth's surface in large quantities; (2) water is readily converted from one state of matter to another (solid, liquid, gas); (3) water's solid phase, ice, is less dense than liquid water; and (4) water has a high heat capacity—meaning changing its temperature requires considerable energy. All these properties influence Earth's weather and climate and are favorable to life as we know it.

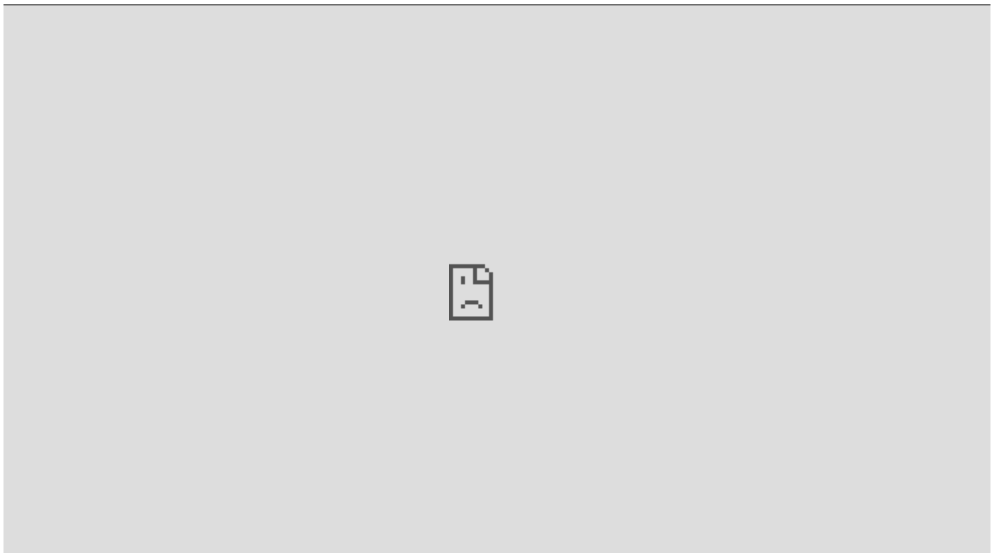
These unique properties are largely a result of water's ability to form hydrogen bonds. **Hydrogen bonds** are the attractive forces that exist between hydrogen atoms in one water molecule and oxygen atoms of any other water molecule. To better grasp the nature of hydrogen bonds, let's examine a water molecule. Water molecules (H_2O) consist of two hydrogen atoms that are strongly bonded to an oxygen atom (Figure 4.2A). Because oxygen atoms have a greater affinity for the bonding electrons (negatively charged subatomic particles) than do hydrogen atoms, the oxygen end of a water molecule acquires a partial negative charge. For the same reason, the hydrogen atoms of a water molecule acquire a partial positive charge. Because oppositely charged particles attract, a hydrogen atom on one water molecule is attracted to an oxygen atom on another water molecule (Figure 4.2B).

Figure 4.2 Hydrogen bonding in water

A. A water molecule consists of one oxygen atom and two hydrogen atoms. **B.** Water molecules are joined together by hydrogen bonds that loosely bond a hydrogen atom on one water molecule with an oxygen atom on another. **C.** Water's solid phase has a crystalline structure.



Watch **Animation: Water Phase Changes**



Hydrogen bonds hold water molecules together to form the solid we call *ice*. In ice, hydrogen bonds produce a rigid hexagonal network (Figure 4.2C). The resulting molecular configuration is very open (lots of empty spaces). When ice is heated sufficiently, it melts. Melting causes some, but not all, of the hydrogen bonds to break. As a result, the water molecules in liquid water display a more compact arrangement and no rigid structure. This explains why water in its liquid phase is denser than it is in the solid phase.

Because ice is less dense than the liquid water beneath it, a water body freezes from the top down. This has far-reaching effects, both for our daily weather and aquatic life. When ice forms on a water body, it insulates the underlying liquid and slows the rate of freezing at depth. If water bodies froze from the bottom, many lakes would freeze solid during the winter, killing its aquatic life. Further, deep bodies of water, such as the Arctic Ocean, would never become ice covered. Such changes in freezing patterns would alter Earth's energy budget, which in turn would modify atmospheric and oceanic circulation patterns.

Water's heat capacity is also related to hydrogen bonding. When water is heated, some of the energy is used to break hydrogen bonds rather than to increase molecular motion. (Recall that an increase in average molecular motion corresponds to an increase in temperature.) Thus, under similar conditions, water heats up and cools down more slowly than most other common substances. As a result, large water bodies tend to moderate temperatures by remaining warmer than adjacent landmasses in winter and cooler in summer, as discussed in Chapter 3.

> Water heats up and cools down more slowly than most other common substances, and as a result, large water bodies tend to moderate temperatures.

Concept Checks 4.1

- Briefly describe the hydrologic cycle.
- Water's solid phase, ice, is less dense than liquid water. Why is this unique property of water important?
- Explain what happens as ice melts to become liquid water.

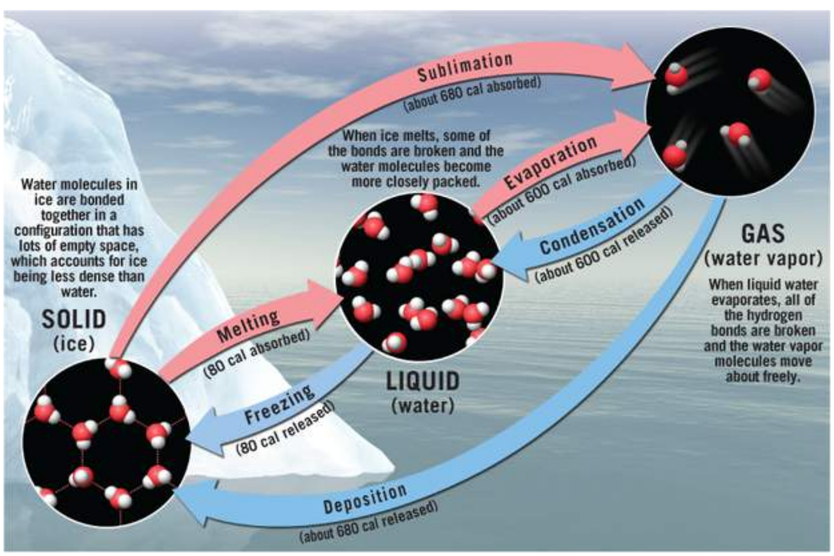
4.2 Water's Changes of State

LO 2 Summarize the six processes by which water changes from one state of matter to another. For each, indicate whether energy is absorbed from or released to the environment.

Water is the only substance that naturally exists on Earth as a solid (ice), liquid, and gas (water vapor). Because all forms of water are composed of hydrogen and oxygen atoms that are bonded together to form water molecules (H_2O), the primary difference among water's three phases is the arrangement of these water molecules (Figure 4.3).

Smartfigure 4.3 Change of state involves an exchange of energy

The amounts shown here are the approximate numbers of calories absorbed or released when 1 gram of water changes from one state of matter to another.



Watch **SmartFigure: Changes of State in Water**

Watch **Video: Global Evaporation Rates**

Ice, Liquid Water, and Water Vapor

Ice is composed of water molecules that have low kinetic energies (motion) and are held together by mutual molecular attractions (hydrogen bonds). These molecules form a tight, orderly network and are not free to move relative to each other; rather, they vibrate within their fixed sites. When ice is heated, the molecules oscillate more rapidly. When the rate of molecular movement increases sufficiently, the hydrogen bonds between some of the water molecules are broken, resulting in melting.

> When water changes state, hydrogen bonds either form or are broken.

In the liquid state, water molecules are still tightly packed but move fast enough to be able to easily slide past one another. As a result, liquid water is fluid and will take the shape of the container that holds it.

When liquid water gains heat from the environment, some of the molecules acquire enough energy to break their hydrogen bonds and escape from the water surface to become water vapor. Water vapor molecules are widely spaced compared to liquid water and exhibit very energetic and random motion.

These processes are reversed when water vapor returns to its liquid state and when water freezes. When water changes state, hydrogen bonds either form or are broken.

Latent Heat

Whenever water changes state, energy is exchanged between water and its surroundings (see Figure 4.3). For example, heat is required to evaporate water. The heat involved when water changes state is measured in units called *calories*. One **calorie** is the amount of energy required to raise the temperature of 1 gram of water 1°C (l.8°F). Thus, when 10 calories of heat are absorbed by 1 gram of water, the molecules vibrate faster, and a 10°C (18°F) temperature increase occurs. (In the International System of Units [SI], joules [J] are used to denote energy; 1 calorie = 4.184 J.)

During a phase change, energy may be added to a substance without an accompanying rise in temperature. For example, when the ice in a glass of ice water melts, the temperature of the mixture remains a constant 0°C (32°F) until all the ice has melted. If the added energy does not raise the temperature of ice water, where does this energy go? In this case, the added energy breaks the hydrogen bonds that once bound the water molecules into a crystalline structure.

Because the energy used to melt ice does not produce a temperature change, it is referred to as **latent heat**. (Latent means *hidden*, like the fingerprints hidden at a crime scene.) The energy, stored in liquid water, is released to its surroundings when the water freezes. In fact, your refrigerator runs more frequently when making ice cubes to counteract the additional energy released during the freezing process.

Melting 1 gram of ice requires 80 calories (334 J), an amount termed the *latent heat of melting*. The reverse process, *freezing*, releases these 80 calories (334 J) per gram to the environment as the *latent heat of fusion*. We will consider the importance of latent heat of fusion in Chapter 5, in the section on frost prevention.

Evaporation and Condensation

Latent heat is also involved in **evaporation**, the process of converting a liquid to a gas (vapor). The energy absorbed by water molecules during evaporation is used to give them the motion needed to escape the surface of the liquid and become a gas. This energy is referred to as the *latent heat of vaporization* and varies from about 600 calories (2500 J) per gram for water at 0°C to 540 calories (2260 J) per gram at 100°C. (Notice in Figure 4.3 that it takes much more energy to evaporate 1 gram of water than it does to melt the same amount of ice.) During the evaporation process, the faster-moving molecules escape the surface. As a result, the average molecular motion (temperature) of the remaining water is lowered—hence the expression "evaporation is a cooling process." You have undoubtedly experienced this cooling effect when you step, dripping wet, out of a swimming pool or shower. In this situation, the energy used to evaporate water comes from your skin—hence, you feel cool.

Condensation, the reverse process, occurs when water vapor changes to the liquid state. During condensation, water vapor molecules release energy (*latent heat of condensation*) in an amount equivalent to what was absorbed during evaporation. When condensation occurs in the atmosphere, it results in the formation of fog or clouds (Figure 4.4A).

Figure 4.4 **Examples of condensation and deposition**

Latent heat plays an important role in many atmospheric processes. In particular, when water vapor condenses to form cloud droplets, latent heat is released, which warms the surrounding air, making it less dense and buoyant. When the moisture content of air is high, this process can spur the growth of towering storm clouds. In addition, the evaporation of water over the tropical oceans and the subsequent condensation at higher latitudes results in significant energy transfer from equatorial regions to more poleward locations. On a smaller scale, when condensation occurs on the outside of a glass filled with ice, the condensation heats the glass and eventually melts the ice.

> The six phase changes of water are: evaporation, condensation, freezing, melting, deposition, and sublimation.

Sublimation and Deposition

You are probably least familiar with the last two processes illustrated in Figure 4.3—sublimation and deposition. **Sublimation** is the conversion of a solid directly to a gas, without passing through the liquid state. Examples you may have observed include the gradual shrinkage of unused ice cubes in a freezer and the rapid conversion of dry ice (frozen carbon dioxide) to wispy clouds that quickly disappear.

Deposition is the reverse process: the conversion of a vapor directly to a solid. An example is water vapor deposited as ice on solid objects such as grass or a window pane (Figure 4.4B). These deposits are called *white frost* or simply *frost*. As shown in Figure 4.3, the process of deposition returns the combined energy released by condensation and freezing to the environment.

You might have wondered . . .

What is "freezer burn"?

Poorly wrapped food stored in a frost-free freezer for an extended time can become "freezer burned." Because modern refrigerators are designed to remove moisture from the freezer compartment, the air inside them is relatively dry. As a result, the moisture in food sublimates—turns from ice to water vapor—and escapes. Thus, the food is not actually burned; it is simply dried out.

Concept Checks 4.2

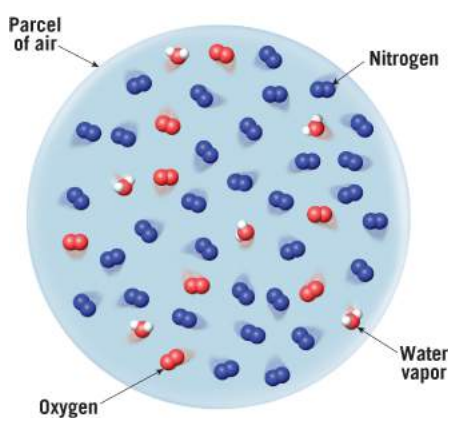
- Summarize the six processes by which water changes from one state to another. Indicate whether heat is absorbed or released in each case.
- Why is evaporation called a cooling process?
- Define *latent heat*, and explain the role that latent heat of condensation plays in the growth of towering clouds.

4.3 Humidity: Water Vapor in the Air

LO 3 Explain the relationship between air temperature and the amount of water vapor needed to saturate air.

Humidity is the general term used to describe the amount of water vapor in the air (Figure 4.5). Water vapor constitutes only a small fraction of the atmosphere, varying from as little as 0.1 percent up to about 4 percent by volume. But the importance of water in the air is far greater than these small percentages indicate. In fact, *water vapor* is the primary source of energy (latent heat) for the formation of weather systems—thunderstorms, tornadoes, and hurricanes.

Figure 4.5 **Meteorologists use several methods to express the water-vapor content of air**



How Is Humidity Expressed?

Meteorologists employ several methods to express the water vapor content of the air, including (1) absolute humidity, (2) mixing ratio, (3) vapor pressure, (4) relative humidity, and (5) dew point. Two of these methods, *absolute humidity* and *mixing ratio*, are similar in that both are expressed as the quantity of water vapor contained in a specific amount of air.

Absolute Humidity

The mass of water vapor in a given volume of air (usually as grams per cubic meter) is known as **absolute humidity**:

$$\text{Absolute humidity} = \frac{\text{Mass of water vapor (grams)}}{\text{Volume of air (cubic meters)}}$$

As air moves from one place to another, changes in pressure and temperature cause changes in its volume. When volume changes, the absolute humidity also changes, even if no water vapor is added or removed. Consequently, it is difficult to monitor the water vapor content of a moving mass of air when using the absolute humidity index. Therefore, meteorologists generally prefer to use mixing ratio to express the water vapor content of air.

Mixing Ratio

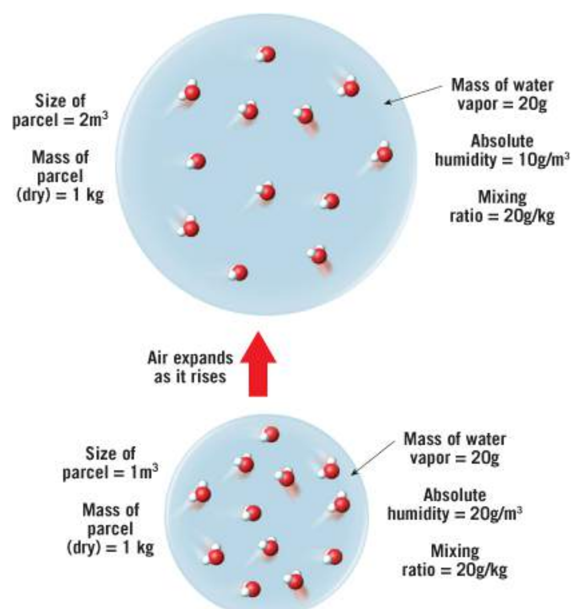
The **mixing ratio** is *the mass of water vapor in a unit of air compared to the remaining mass of dry air*:

$$\text{Mixing ratio} = \frac{\text{Mass of water vapor (grams)}}{\text{Mass of dry air (kilograms)}}$$

Because it is measured in units of mass (usually grams per kilogram), the mixing ratio is not affected by changes in pressure or temperature (Figure 4.6).*

Figure 4.6 Comparison of absolute humidity and mixing ratio for a rising parcel of air

Notice that the mixing ratio is not affected by changes in pressure as the parcel of air rises and expands.

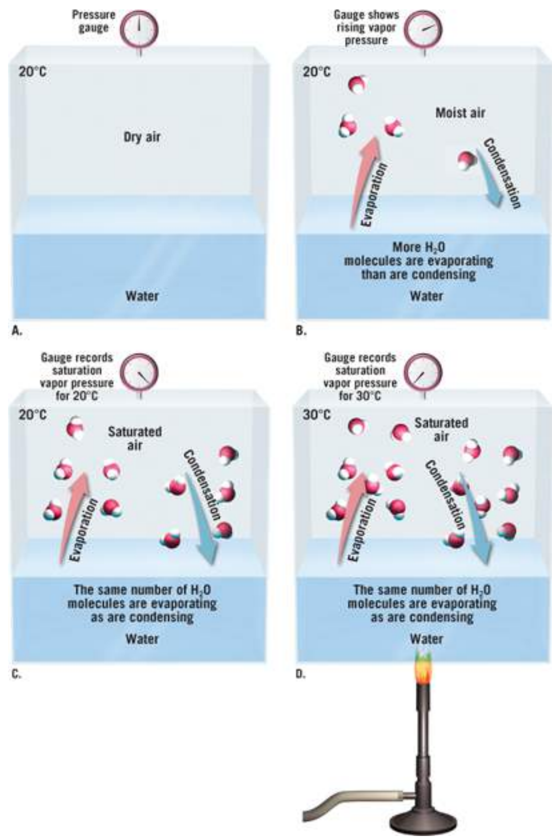


Vapor Pressure and Saturation

We can determine the moisture content of the air from the pressure exerted by water vapor. To understand how water vapor exerts pressure, imagine a closed flask containing pure water and overlain by dry air, as shown in Figure 4.7A. Almost immediately some of the water molecules begin to leave the water surface and evaporate into the dry air above. The addition of water vapor into the air can be detected by a small increase in pressure (Figure 4.7B). This increase in pressure is a result of the motion of the water vapor molecules that were added to the air through evaporation. This pressure, called **vapor pressure**, is defined as *that part of the total atmospheric pressure attributable to its water vapor content*.

Figure 4.7 **The relationship between vapor pressure and saturation**

A. Initial conditions—dry air at 20°C with no observable vapor pressure. **B.** Evaporation generates measurable vapor pressure. **C.** As more and more molecules escape from the water surface, the steadily increasing vapor pressure forces an increasing number of molecules to return to the liquid. Eventually, the number of water-vapor molecules returning to the surface will balance the number leaving—at which point the air is said to be saturated. **D.** When the container is heated from 20°C to 30°C, the rate of evaporation increases, causing the vapor pressure to increase until a new balance is reached.



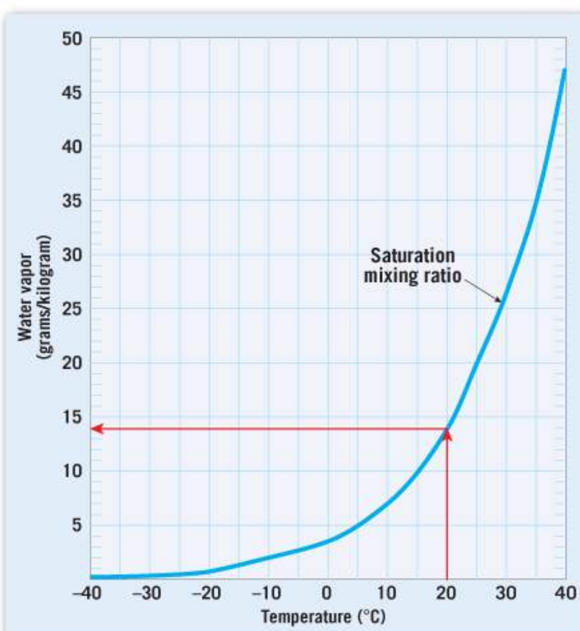
Initially, many more molecules will leave the water surface (evaporate) than will return (condense). However, as more and more molecules evaporate from the water surface, the steadily increasing vapor pressure in the air above forces more and more water molecules to return to the liquid. Eventually a balance is reached in which the number of water molecules returning to the surface equals the number leaving. At that point, the air is said to have reached an equilibrium called **saturation** (Figure 4.7C). When air is saturated, the pressure exerted by the motion of the water vapor molecules is called the **saturation vapor pressure**.

> Vapor pressure is that part of the total atmospheric pressure attributable to its water vapor content.

If the water in the closed container is heated, the equilibrium between evaporation and condensation will be disrupted, as illustrated in Figure 4.7D. The added energy increases the rate of evaporation, which causes the vapor pressure in the air above to increase, until a new equilibrium is reached. Thus, we can conclude that the saturation vapor pressure is temperature dependent, such that at higher temperatures it takes more water vapor to saturate air (Figure 4.8).

Figure 4.8 Graph illustrating the amount of water vapor required to saturate 1 kilogram of dry air at various temperatures

For example, the red arrows show that saturated air at 20°C contains 14 grams of water vapor per kilogram of dry air.



> When air is saturated, the pressure exerted by the motion of the water vapor molecules is called the saturation vapor pressure.

The amount of water vapor required to saturate 1 kilogram (2.2 pounds) of dry air at various temperatures is shown in Table 4.1. Note that for every 10°C (18°F) increase in temperature, the amount of water vapor needed for saturation almost doubles. Thus, roughly four times more water vapor is needed to saturate 30°C (86°F) air than 10°C (50°F) air.

Table 4.1 Saturation Mixing Ratio (at Sea-Level Pressure)

Temperature, °C (°F)	Saturation Mixing Ratio, g/kg
–40 (–40)	0.1
–30 (–22)	0.3
–20 (–4)	0.75
–10 (14)	2
0 (32)	3.5
5 (41)	5
10 (50)	7
15 (59)	10
20 (68)	14
25 (77)	20
30 (86)	26.5
35 (95)	35
40 (104)	47

The atmosphere behaves in much the same manner as our closed container. In nature, gravity, rather than a lid, prevents water vapor (and other gases) from escaping into space. Also as with our container, water molecules are constantly evaporating from liquid surfaces (such as lakes or oceans), and other water vapor molecules are condensing (into cloud droplets or dew). However, in nature, a balance is not always achieved. More often than not, more water molecules are leaving the surface of a water puddle than are arriving. By contrast, during the formation of fog, more water molecules are condensing than are evaporating from the tiny fog droplets.

What determines whether the rate of evaporation exceeds the rate of condensation or vice versa? One major factor is the temperature of the water, which in turn determines how much motion (kinetic energy) the water molecules possess. At higher temperatures, water molecules have more energy and can more readily escape.

Eye on the Atmosphere 4.1

Water is everywhere on Earth—in the oceans, glaciers, rivers, lakes, air, and living tissue. In addition, water can change from one state of matter to another at the temperatures and pressures experienced on Earth. Refer to this image, taken above the Grand Tetons in Wyoming, to answer the following questions.

Apply What You Know

1. What feature in this photo is composed of water in the liquid state?
2. Name the process by which ice changes directly from a solid to water vapor.
3. Identify where water vapor is found in this image.

Vapor pressure is the other major factor that determines whether evaporation or condensation is the dominant process. Recall from our closed container example that vapor pressure influences the rate at which the water molecules leave (evaporate) and also the rate at which they return to the surface (condense). When the air is dry (low vapor pressure), the rate at which water molecules escape from a liquid surface is high. As the vapor pressure increases, the rate at which water vapor returns to the liquid phase increases as well.

You might have wondered . . .

Why do snow piles seem to shrink a few days after a snowfall, even when the temperatures remain below freezing?

On clear, cold days following a snowfall, the air can be very dry. This fact, plus solar heating, causes the ice crystals to sublimate—turn from a solid to a gas. Thus, even without any appreciable melting, these accumulations of snow gradually get smaller.

Concept Checks 4.3

- How do absolute humidity and mixing ratio differ? What do they have in common?
- Define *vapor pressure*, and describe the relationship between vapor pressure and saturation. (*Hint:* See Figure 4.7.)
- After reviewing Table 4.1, summarize the relationship between air temperature and the amount of water vapor needed to saturate air.

* Another commonly used expression is *specific humidity*, which is the mass of water vapor in a unit mass of air, including the water vapor. Because water vapor constitutes just a few percent of the total mass, specific humidity is equivalent to the mixing ratio for all practical purposes.

4.4 Relative Humidity and Dew-Point Temperature

LO 4 List and describe the ways relative humidity changes in nature. Compare relative humidity to dew-point temperature.

The most familiar and, unfortunately, the most misunderstood term used to describe the moisture content of air is relative humidity. **Relative humidity** *is a ratio of the air's actual water vapor content compared with the amount of water vapor required for saturation at that temperature (and pressure)*. Thus, relative humidity measures how near the air is to saturation rather than the actual quantity of water vapor in the air (Box 4.1). Relative humidity can be expressed as follows:*

$$\text{Relative humidity} = \frac{\text{Mixing ratio (actual water vapor in the air, g/kg)}}{\text{Saturation mixing ratio (maximum water vapor the air can hold, g/kg)}} \times 100\%$$

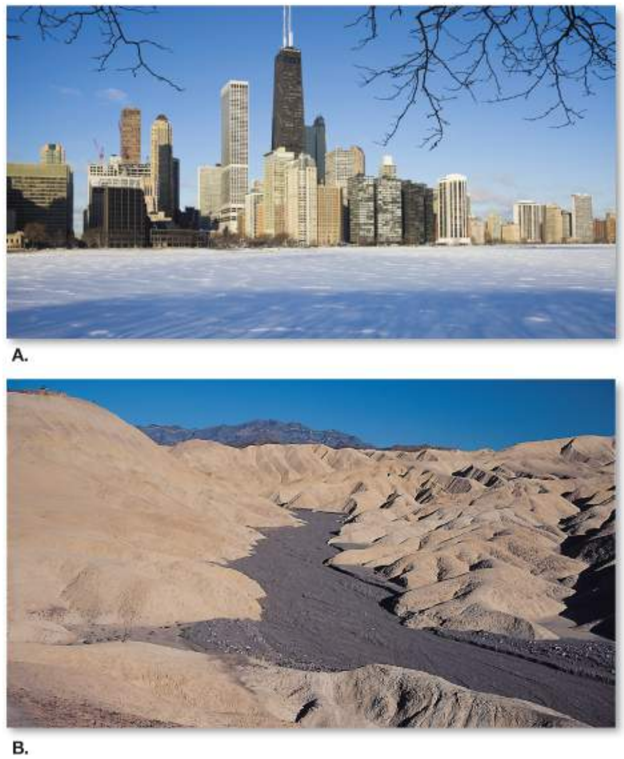
Box 4.1

Dry Air at 100 Percent Relative Humidity?

A common misconception is the notion that air with a higher relative humidity has greater water-vapor content than air with a lower relative humidity. This is not always the case (Figure 4.A). Compare a typical January day in Chicago, Illinois, to one in the desert of Death Valley, California. On this hypothetical day, the temperature in Chicago is a cold −10°C (14°F), and the relative humidity is 100 percent. By referring to Table 4.1, we can see that saturated −10°C air has a water-vapor content (mixing ratio) of 2 grams per kilogram (g/kg). By contrast, the desert air at Death Valley on this January day is a warm 25°C (77°F), and the relative humidity is just 20 percent. A look at Table 4.1 reveals that 25°C air has a saturation mixing ratio of 20 g/kg. Therefore, with a relative humidity of 20 percent, the air at Death Valley has a water-vapor content of 4 g/kg (20 grams × 20 percent). Consequently, the “dry” air in Death Valley actually contains twice the water vapor as the air in Chicago, with a relative humidity of 100 percent.

Figure 4.A

Moisture content of frigid air versus hot air. Frigid air with a high relative humidity (A) generally has a lower water-vapor content than hot desert air with a low relative humidity (B).



This example illustrates that very cold places are also very dry. The low water-vapor content of frigid air (even when saturated) helps explain why many arctic areas receive only meager amounts of precipitation and are referred to as “polar deserts.” This also helps us understand why people frequently experience dry skin and chapped lips during the winter months. The water-vapor content of cold air is low, even compared to some hot, arid regions.

Apply What You Know

1. Assume that two locations, one colder than the other, have the same relative humidity (50 percent). At which location will the water-vapor content of the air be higher? How do you know?

* Relative humidity can also be expressed as:

$$\mathrm{RH} = \frac{\text{vapor pressure}}{\text{Saturated vapor pressure}} \times 100\%$$

How Relative Humidity Changes

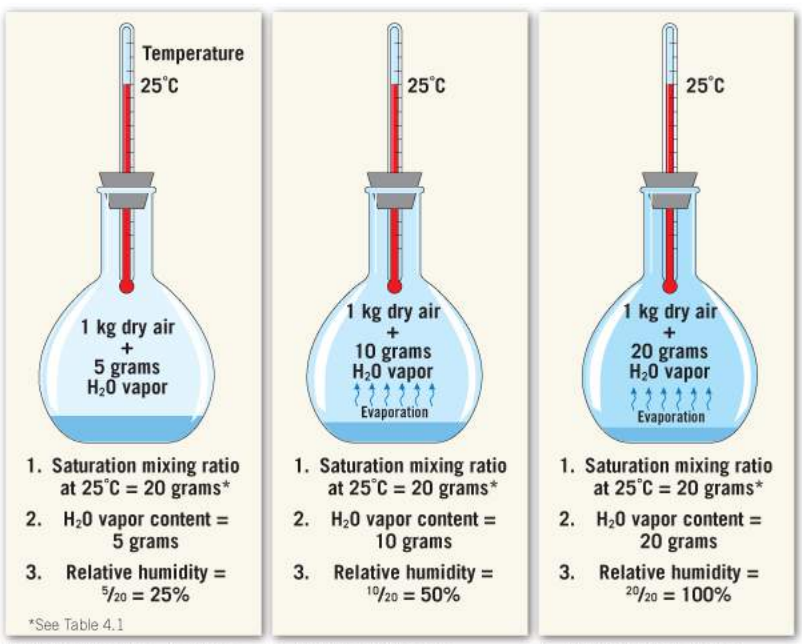
Because relative humidity is based on the air's water-vapor content, as well as the amount of moisture required for saturation, it can change in one of two ways. First, relative humidity changes when water vapor is added to or removed from the atmosphere. Second, because the amount of moisture required for saturation is a function of air temperature, relative humidity varies with temperature.

How Changes in Moisture Affect Relative Humidity

Notice in Figure 4.9 that when water vapor is added to air through evaporation, the relative humidity of the air increases until saturation occurs (100 percent relative humidity). What if even more moisture is added to this parcel of saturated air? Does the relative humidity exceed 100 percent? In the lower atmosphere, this situation is rare. Instead, the excess water vapor condenses to form liquid water. (Note that supersaturation—RH above 100 percent—often occurs in the middle and upper troposphere, and is addressed in Chapter 5.)

Figure 4.9 At a constant temperature (in this example, it is 25°C), the relative humidity will increase as water vapor is added to the air

The saturation mixing ratio for air at 25°C is 20 g/kg (see Table 4.1). As the water-vapor content in the flask increases, the relative humidity rises from 25 percent in **A** to 100 percent in **C**.



A. Initial condition: 5 grams of water vapor

B. Addition of 5 grams of water vapor = 10 grams

C. Addition of 10 grams of water vapor = 20 grams

You may have experienced saturation conditions while taking a hot shower. The water is composed of very energetic (hot) molecules, which means that the rate of evaporation is high. As long as you run the shower, the process of evaporation continually adds water vapor to the unsaturated air in the bathroom. If that hot water runs for enough time, the air eventually becomes saturated, which makes the air foggy.

In nature, moisture is added to the air mainly via evaporation from the oceans. However, plants, soil, and smaller bodies of water also make substantial contributions. Unlike with your shower, however, the natural processes that add water vapor to the air generally do not operate at rates fast enough to cause saturation to occur directly. One exception is when you exhale on a cold winter day and "see your breath": The warm, moist air from your lungs mixes with the cold outside air. Your breath has enough moisture to saturate a small quantity of cold outside air, producing a miniature "cloud." Almost as fast as the "cloud" forms, it mixes with the surrounding dry air and evaporates.

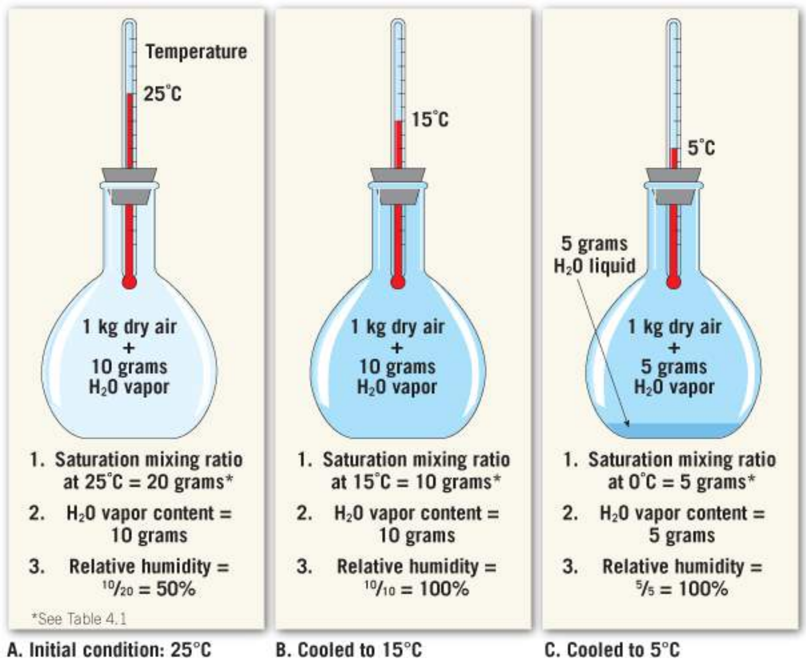
> Increasing moisture or decreasing temperature both result in an increase in relative humidity.

How Relative Humidity Changes with Temperature

The second condition that affects relative humidity is air temperature. Examine Figure 4.10A carefully, and note that when air at 25°C contains 10 grams of water vapor per kilogram, it has a relative humidity of 50 percent. When the flask in Figure 4.10A is cooled from 25° to 15°C, as shown in Figure 4.10B, the relative humidity increases from 50 to 100 percent. We can conclude that when the water-vapor content remains constant, *a decrease in temperature results in an increase in relative humidity*. In the shower example, the bathroom gets foggy when the air is saturated, but the mirror becomes foggy more quickly than the air in the bathroom. This is because the mirror is cooler than the moist air in the room and cools the adjacent air sufficiently to cause condensation directly on the mirror.

Figure 4.10 **Relative humidity varies with temperature**

When the water-vapor content (mixing ratio) remains constant, the relative humidity will change when the air temperature either increases or decreases. In this example, when the temperature of the air in the flask was lowered from 25°C in **A** to 15°C in **B**, the relative humidity increased from 50 to 100 percent. Further cooling from 15°C in **B** to 5°C in **C** causes one-half of the water vapor to condense. In nature, when saturated air cools, it causes condensation in the form of clouds, dew, or fog.



But there is no reason to assume that cooling would cease the moment the air reached saturation. What happens when the air is cooled below the temperature at which saturation occurs? Figure 4.10C illustrates this situation. Notice from Table 4.1 that when the flask is cooled to 5°C, the air is saturated, at 5 grams of water vapor per kilogram of air. Because this flask originally contained 10 grams of water vapor, 5 grams of water vapor will condense to form liquid droplets that collect on the walls of the container. In the meantime, the relative humidity of the air inside remains at 100 percent. This illustrates an important concept: When air aloft is cooled below its saturation level, some of the water vapor condenses to form clouds. Since clouds are made of liquid droplets (or ice crystals), this moisture is no longer part of the water-vapor content of the air.

Conversely, *an increase in temperature results in a decrease in relative humidity*. For example, assume that the flask in Figure 4.10A containing 10 grams of water vapor is heated from 25°C to 40°C. Table 4.1 indicates that at 40°C, saturation occurs at 47 grams of water vapor per kilogram of air. Consequently, when the air is heated from 25° to 40°C, the relative humidity will drop from 10/20 (or 50 percent) to 10/47 (or about 21 percent).

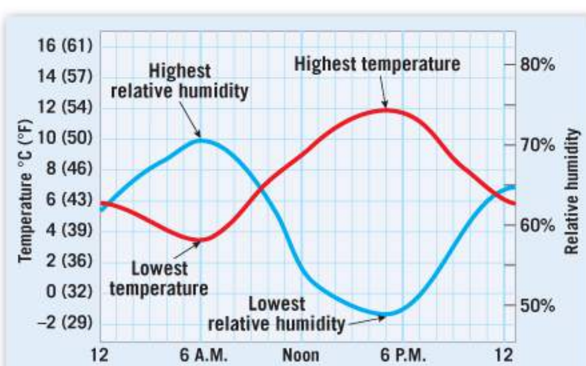
Natural Changes in Relative Humidity

In nature there are three major ways that air temperatures change (over relatively short time spans) to cause corresponding changes in relative humidity:

- Daily changes in temperatures (daylight versus nighttime temperatures)
- Temperature changes that result when air moves horizontally from one location to another
- Temperature changes caused when air moves vertically in the atmosphere

The effect of the first of these three processes (daily changes) is shown in Figure 4.11. Notice that during midafternoon, relative humidity reaches its lowest level, whereas the cooler evening hours are associated with higher relative humidity. In this example, the actual water-vapor content (mixing ratio) of the air remains unchanged; only the relative humidity varies. We will consider the other two processes in more detail in later chapters.

Figure 4.11 Typical daily variation in temperature and relative humidity during a spring day in Washington, DC



Dew-Point Temperature

The **dew-point temperature**, or simply the **dew point**, is *the temperature at which water vapor begins to condense*. The term *dew point* stems from the fact that during nighttime hours, objects near the ground often cool below the dew-point temperature and become coated with dew. You have undoubtedly seen "dew" form on an ice-cold drink on a humid summer day (Figure 4.12). Near Earth's surface, when the air is cooled below its dew-point temperature it generates *dew* or *fog*—if the dew point is above freezing. By contrast, when the dew-point temperature is below freezing (0°C, 32°F) *frost* occurs.

Figure 4.12 Condensation and dew-point temperature

Condensation, or "dew," occurs when a cold drinking glass chills the surrounding layer of air below the dew-point temperature.

You might have wondered . . .

Why do my lips get chapped in the winter?

During the winter months, outside air is comparatively cool and dry. When this air is drawn into a home, it is heated, which causes the relative humidity to plunge. Unless your home is equipped with a humidifier, you are likely to experience chapped lips and dry skin at that time of year.

Dew point can also be defined as the *temperature at which air reaches saturation* and, hence, is directly related to the *actual moisture content* of a parcel of air. Recall that the saturation vapor pressure is temperature dependent and that for every 10°C (18°F) increase in temperature, the amount of water vapor needed for saturation doubles. Therefore, cold saturated air (0°C [32°F]) contains about half the water vapor of saturated air having a temperature of 10°C (50°F) and roughly one-fourth that of saturated air with a temperature of 20°C (68°F). Because the dew point is the temperature at which saturation occurs, we can conclude that high dew-point temperatures equate to moist air and, conversely, low dew-point temperatures indicate dry air (Table 4.2). More precisely, based on what we have learned about vapor pressure and saturation, we can state that for every 10°C (18°F) increase in the dew-point temperature, air contains about twice as much water vapor. Therefore, we know that when the dew-point temperature is 25°C (77°F), air contains about twice the water vapor as when the dew point is 15°C (59°F) and four times that of air with a dew point of 5°C (41°F).

Table 4.2 Dew-Point Thresholds

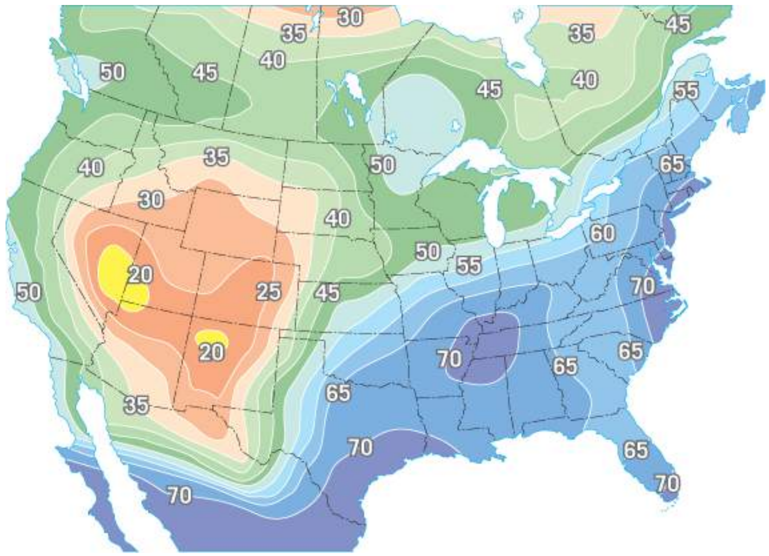
Dew-Point Temperature	Threshold
≤ 10°F	Significant snowfall is inhibited
≥ 55°F	Minimum for severe thunderstorms to form
≥ 65°F	Considered humid by most people
≥ 70°F	Typical of the rainy tropics
≥ 75°F	Considered oppressive by most

> Dew point is the temperature at which air reaches saturation.

Because the dew-point temperature is a good measure of the amount of water vapor in the air, it commonly appears on weather maps. When the dew point exceeds 65°F (18°C), most people consider the air to feel humid; air with a dew point of 75°F (24°C) or higher is considered oppressive. Notice on the map in Figure 4.13 that much of the southeastern United States has dew-point temperatures that exceed 65°F (18°C). Also notice in Figure 4.13 that although the Southeast is dominated by humid conditions, most of the remainder of the country is experiencing comparatively drier air.

Smartfigure 4.13 **Surface map showing dew-point temperatures for a typical September day**

Dew-point temperatures above 60°F dominate the southeastern United States, indicating that this region is blanketed with humid air.



Watch **SmartFigure: Dewpoint**

How Is Humidity Measured?

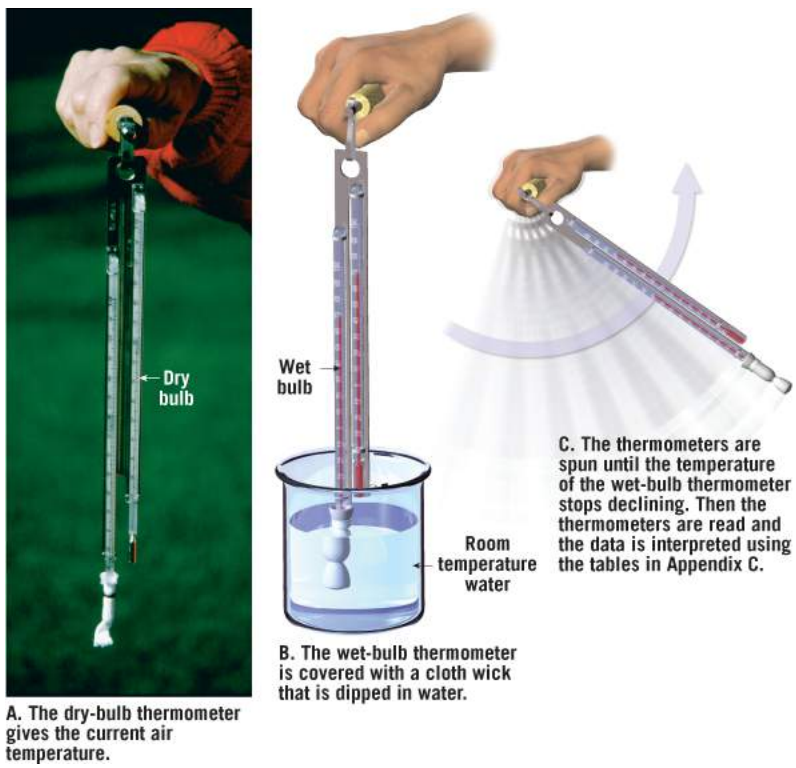
Instruments called **hygrometers** are used to measure the moisture content of the air. In addition to being used in meteorology, hygrometers are used in greenhouses, humidors, museums, and numerous industrial settings that are sensitive to humidity, such as paint booths where protective coatings are applied to products. Because it is difficult to directly measure absolute humidity and the mixing ratio, most hygrometers measure either relative humidity or dew-point temperature. Once either of these is known, it is relatively easy to convert to any of the other humidity measurements as long as we know the temperature.

Psychrometers

One of the simplest hygrometers, a **psychrometer** (called a *sling psychrometer* when connected to a handle and spun) consists of two identical thermometers mounted side by side (Figure 4.14A). One thermometer, called the *dry bulb*, measures air temperature, and the other, called the *wet bulb*, has a thin cloth wick tied at the bottom. This cloth wick is saturated with water, and a continuous current of air is passed over the wick, either by swinging the psychrometer or by using an electric fan to move air past the instrument (Figure 4.14B,C). As a result, water evaporates from the wick, absorbing heat energy from the wet-bulb thermometer, which causes its temperature to drop. The amount of cooling that takes place is directly proportional to the dryness of the air: The drier the air, the greater the cooling. Therefore, the larger the difference between the wet- and dry-bulb temperatures, the lower the relative humidity. By contrast, if the air is saturated, no evaporation will occur, and the two thermometers will have identical readings. By using a psychrometer and the tables provided in Appendix C, you can easily determine the relative humidity and the dew-point temperature.

Figure 4.14 Sling psychrometer

A. A sling psychrometer consists of one dry-bulb thermometer and one wet-bulb thermometer. **B.** The dry-bulb thermometer measures the current air temperature. The wet-bulb thermometer is covered with a cloth wick dipped in water. **C.** As the instrument is spun, evaporation cooling causes the temperature of the wet-bulb thermometer to decrease. The amount of cooling that occurs is directly proportional to the dryness of the air. The temperature difference between the dry- and wet-bulb thermometers is used in conjunction with the tables in Appendix C to determine relative humidity and dew-point temperature.



Hair Hygrometers

One of the oldest instruments used for measuring relative humidity, called a *hair hygrometer*, operates on the principle that hair changes length in proportion to changes in relative humidity. Hair lengthens as relative humidity increases and shrinks as relative humidity drops. People with naturally curly hair experience this phenomenon: In humid weather their hair lengthens and hence becomes curlier. A hair hygrometer uses a bundle of hairs linked mechanically to an indicator that is calibrated between 0 and 100 percent. However, these instruments have become largely obsolete as more accurate tools have been developed.

> Hygrometers are instruments that measure the quantity of moisture in the air.

Electric Hygrometers

Today, a variety of *electric hygrometers* are widely used to measure humidity. One type of electric hygrometer uses a chilled mirror and a mechanism that detects the temperature at which condensation begins to form on the mirror. Thus, a *chilled mirror hygrometer* measures the dew-point temperature of the air.

The Automated Weather Observing System (AWOS) operated by the National Weather Service (NWS) employs an electric hygrometer that works on the principle of *capacitance*—a material's ability to store an electrical charge. The sensor consists of a thin hygroscopic (water-absorbent) film that is connected to an electric current. As the film absorbs or releases water the capacitance of the sensor changes at a rate proportional to the relative humidity of the surrounding air. Thus, relative humidity can be measured by monitoring the change in the film's capacitance. Higher capacitance equates to higher relative humidity.

Concept Checks 4.4

- How is relative humidity different from absolute humidity and the mixing ratio?
- Refer to Figure 4.11 and describe the relationship between the daily cycle of temperature and the cycle of relative humidity if the dew-point temperature is constant.
- Which measure of humidity, relative humidity or dew point, best describes the actual quantity of water vapor in a mass of air?

4.5 Adiabatic Temperature Changes and Cloud Formation

LO 5 Describe adiabatic temperature changes and explain why the wet adiabatic rate of cooling is less than the dry adiabatic rate.

Recall that condensation occurs when sufficient water vapor is added to the air or, more commonly, when the air is cooled to its dew-point temperature. Condensation may produce dew, fog, or clouds. Heat near Earth's surface is readily exchanged between the ground and the air directly above. As the ground loses heat in the evening (radiation cooling), dew may condense on the grass, while fog may form slightly above Earth's surface. Thus, surface cooling that occurs after sunset produces some condensation. Cloud formation, however, often takes place during the warmest part of the day—an indication that another mechanism must operate aloft that cools air sufficiently to generate clouds.

The process that generates most clouds is easily visualized. Have you ever pumped up a bicycle tire with a hand pump and noticed that the pump barrel became very warm? When you applied energy to *compress* the air, the motion of the gas molecules increased, and the temperature of the air rose. Conversely, if you allow air to escape from a bicycle tire, the air *expands*; the gas molecules move less rapidly, and the air cools. You have probably felt the cooling effect of expanding propellant gas as you applied hair spray or spray deodorant. The temperature changes just described, in which heat energy is neither added nor subtracted, are called **adiabatic temperature changes**: that is, temperature changes that result from changes in pressure rather than changes in heat energy.

When air is compressed, it warms, and when air is allowed to expand, it cools.

Adiabatic Cooling and Condensation

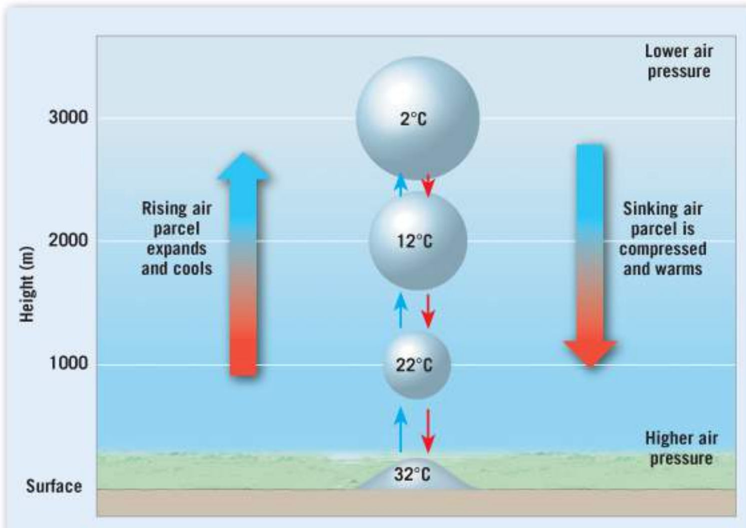
To simplify the discussion of adiabatic cooling, imagine a volume of air enclosed in a thin balloon-like bubble. Meteorologists call this imaginary volume of air a **parcel**. Typically, we consider a parcel to be a few hundred cubic meters in volume, and we assume that it acts independently of the surrounding air. It is also assumed that no heat is transferred into or out of the parcel. Although this image is highly idealized, over short time spans, a parcel of air behaves much like an actual volume of air moving up or down in the atmosphere.

> Temperature changes due to increasing or decreasing pressure, rather than the addition or subtraction of heat energy, are called adiabatic temperature changes.

Recall from Chapter 1 that atmospheric pressure decreases with height. Any time a parcel of air moves upward, it passes through regions of successively lower pressure. As a result, ascending air expands and cools adiabatically. Unsaturated air cools at a constant rate of 10°C for every 1000 meters of ascent (5.5°F per 1000 feet). Conversely, descending air undergoes increasing pressure and is compressed and heated 10°C for every 1000 meters of descent (Figure 4.15). This rate of cooling or heating applies only to *unsaturated air* and is known as the **dry adiabatic rate** ("dry" because the air is unsaturated).

Figure 4.15 Dry adiabatic rate of cooling and heating

Whenever an unsaturated parcel of air is lifted, it expands and cools at the *dry adiabatic rate* of 10°C per 1000 meters. Conversely, when air sinks, it is compressed and heats at the same rate.

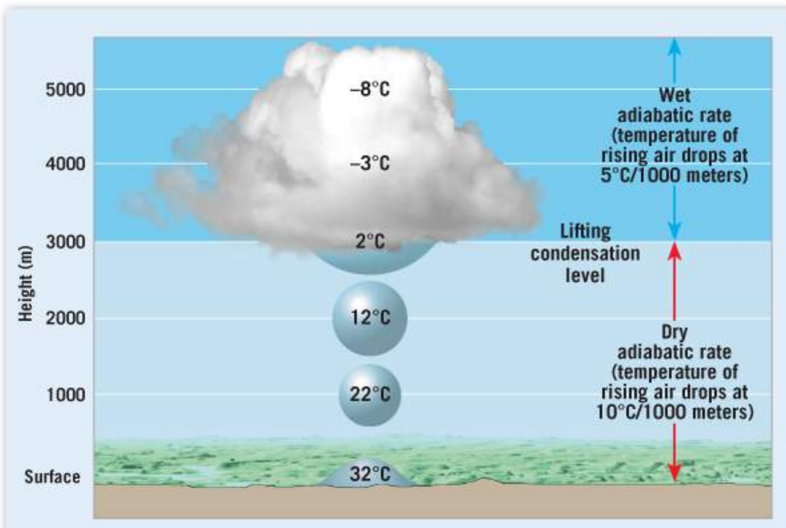


If an air parcel rises high enough, it will eventually cool to its dew point and trigger the process of condensation. The altitude at which a parcel reaches saturation and cloud formation begins is called the **lifting condensation level (LCL)**. At the lifting condensation level, an important change occurs: The *latent heat* that was absorbed by the water vapor when it evaporated is released as *sensible heat*—energy that can be measured with a thermometer—as condensation takes place. Although the parcel will continue to cool adiabatically, the release of latent heat slows the rate of cooling. In other words, when a parcel of air ascends above the lifting condensation level, the rate at which it cools is reduced. This slower rate of cooling is called the **wet adiabatic rate** (also commonly termed the *moist* or *saturated adiabatic rate*).

The amount of latent heat released depends on the quantity of moisture present in the air (generally between 0 and 4 percent). Therefore, the wet adiabatic rate varies from 5°C per 1000 meters for air with a high moisture content to 9°C per 1000 meters for air with a low moisture content. Figure 4.16 illustrates the role of adiabatic cooling in the formation of clouds.

Figure 4.16 Lifting condensation level and the wet adiabatic rate

Rising air expands and cools at the dry adiabatic rate of 10°C per 1000 meters until the air reaches the dew point (2°C for the air parcel pictured) and condensation (cloud formation) begins. As air continues to rise, the latent heat released by condensation reduces the rate of cooling. The wet adiabatic rate is therefore always less than the dry adiabatic rate.



Rising air cools at the dry adiabatic rate, from Earth's surface up to the lifting condensation level—at which point the air cools at the wet adiabatic rate.

Concept Checks 4.5

- Why does air expand as it moves upward through the atmosphere?
- At what rate does unsaturated air cool when it rises through the atmosphere?
- Why does the adiabatic rate of cooling change when condensation begins?

4.6 Processes That Lift Air

LO 6 Identify four mechanisms that cause air to rise.

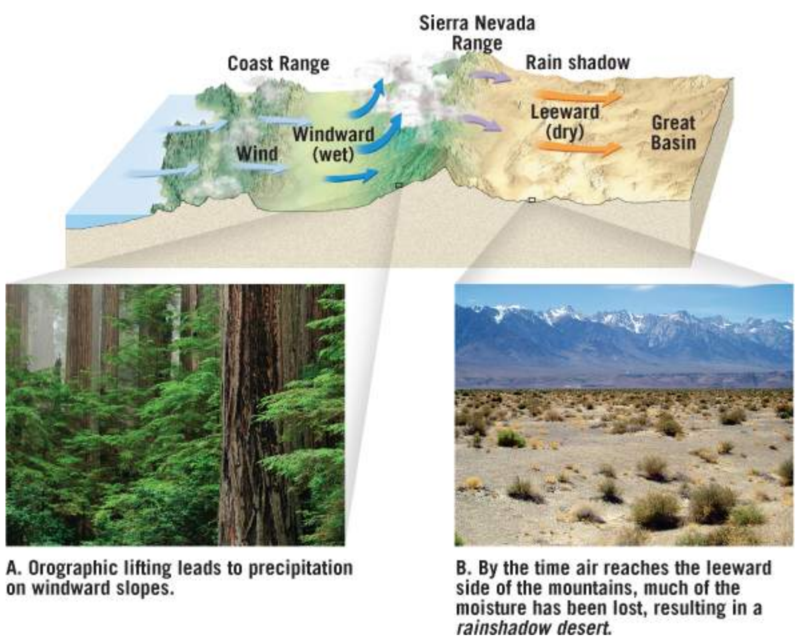
Although air tends to resist vertical movement (air near the surface "wants" to stay near the surface, a condition discussed in section 4.7), there are several mechanisms that cause air to rise and trigger the formation of clouds. These mechanisms include orographic lifting, frontal lifting, convergence, and localized convective lifting.

Orographic Lifting

Orographic lifting occurs when elevated terrain, such as mountains, act as barriers to the horizontal flow of air (Figure 4.17). As air ascends a mountain slope, adiabatic cooling often generates clouds and copious precipitation. In fact, many of the rainiest places in the world are located on windward mountain slopes (Box 4.2).

Figure 4.17 **Orographic lifting and precipitation**

A. Orographic lifting leads to precipitation on windward slopes of a topographic barrier, such as a mountain. **B.** By the time air reaches the leeward side of the mountains, much of the moisture has been lost. The Great Basin desert is a rain shadow desert that covers nearly all of Nevada and portions of adjacent states.



Box 4.2

Precipitation Records and Mountainous Terrain

Many of the rainiest places in the world are located on windward mountain slopes. Typically, these areas are rainy because mountains act as barriers to Earth's natural circulation. The prevailing winds are forced to ascend the sloping terrain, thereby generating clouds and often abundant precipitation. Mount Waialeale, Hawaii, for example, records the highest average annual rainfall in the world, some 1234 centimeters (486 inches). The station is located on the windward (northeastern) coast of the island of Kauai, at an elevation of 1569 meters (5148 feet). By contrast, only 31 kilometers (19 miles) away lies sunny Barking Sands, with annual precipitation averaging less than 50 centimeters (20 inches).

The largest recorded rainfall for a 12-month period occurred at Cherrapunji, India, where an astounding 2647 centimeters (1042 inches), over 86 feet, fell from August 1860 through July 1861. Most of this rainfall occurred in July. By comparison, 10 times more rain fell in a *month* at Cherrapunji, India, than falls in Chicago in an average *year*. Cherrapunji's location just north of the Bay of Bengal and its elevation of 1293 meters (4309 feet) makes it an ideal location to receive the full effect of India's wet summer monsoons.

Because mountains receive abundant precipitation, they are typically very important sources of water, especially for many dry locations in the western United States. The snow pack that accumulates high in the mountains during the winter is a major source of water for the summer season, when precipitation is light and demand for water is great (Figure 4.B). The record for greatest annual snowfall in the United States goes to the Mount Baker ski area north of Seattle, Washington, where 2896 centimeters (1140 inches) of snow fell during the winter of 1998–1999.

Figure 4.B

This heavy snowpack is at Gotthard Pass in the Swiss Alps.

Apply What You Know

1. What location has the record for the highest average annual rainfall in the world?

By the time air reaches the leeward side of a mountain, much of its moisture has been lost. If the air descends, it warms adiabatically, making condensation and precipitation even less likely. As shown in Figure 4.17, the result can be a **rain shadow desert** (look ahead to Box 4.4). The Great Basin Desert of the western United States lies only a few hundred kilometers from the Pacific Ocean, but it is effectively cut off from the ocean's moisture by the imposing Sierra Nevada (Figure 4.17). The Gobi Desert of Mongolia, the Takla Makan of China, and the Patagonia Desert of Argentina are other examples of rain shadow deserts located on the leeward sides of large mountain systems.

> Orographic lifting occurs when air is forced to rise over a mountainous barrier.

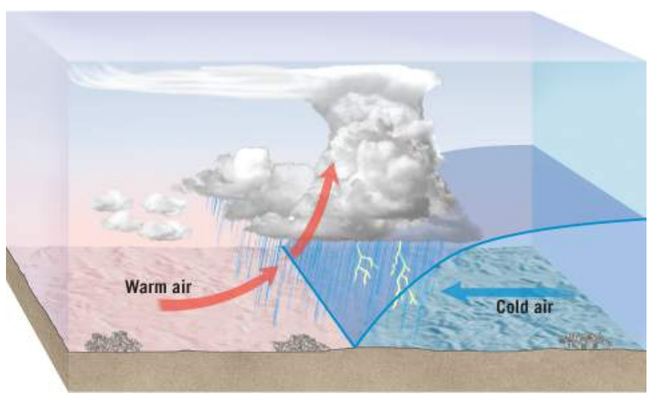
Frontal Lifting

If orographic lifting were the only mechanism that forced air aloft, the relatively flat central portion of North America would be an expansive desert rather than the area known as “the nation’s breadbasket.” Fortunately, this is not the case.

In central North America, warm and cold air masses often collide, producing boundaries called **fronts**. Rather than mixing, the cooler, denser air mass acts as a barrier over which the warmer, less dense air mass rises. This process, called **frontal lifting**, also referred to as **frontal wedging**, is illustrated in Figure 4.18.

Figure 4.18 Frontal lifting

Colder, denser air acts as a barrier over which warmer, less dense air rises.



It should be noted that weather-producing fronts are associated with storm systems called *midlatitude cyclones*. Because these storms are responsible for producing a high percentage of the precipitation in the middle latitudes, we will examine them in detail in Chapter 9.

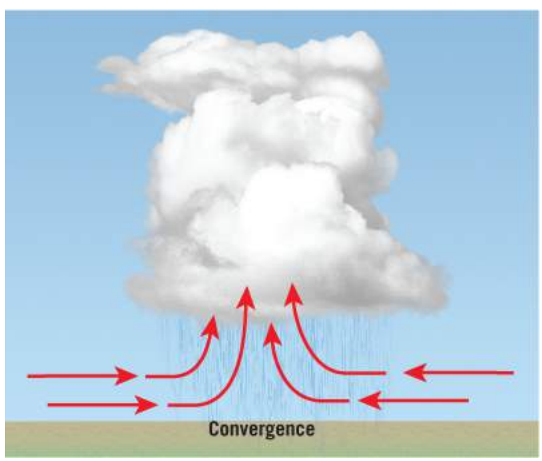
> Frontal lifting is a mechanism whereby warmer, less dense air is forced over cooler, denser air.

Convergence

When the wind pattern near Earth's surface is such that more air is entering an area than is leaving—a phenomenon called **convergence**—lifting occurs (Figure 4.19). Convergence as a mechanism of lifting is most often associated with large centers of *low pressure*, mainly midlatitude cyclones and hurricanes. The inward flow of air at the surface of these systems is balanced by rising air, cloud formation, and usually precipitation.

Figure 4.19 Convergence at the surface causes air to rise

When the wind pattern near Earth's surface is such that more air is entering an area than is leaving—a phenomenon called convergence—lifting occurs.

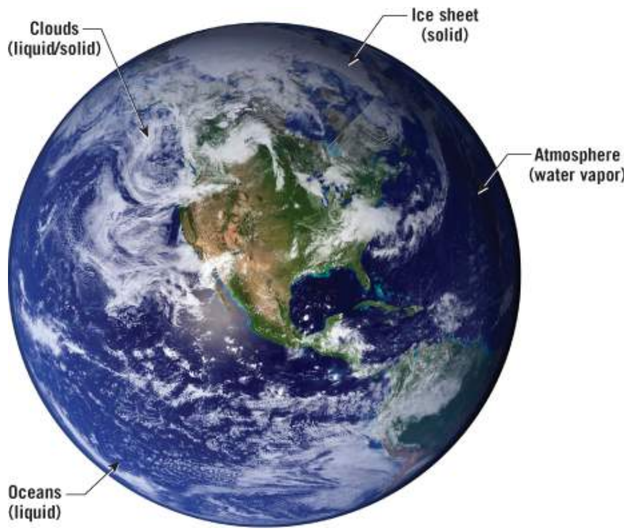


Convergence can also occur when an obstacle slows or restricts horizontal airflow (wind). For example, when air moves from a relatively smooth surface, such as the ocean, onto an irregular landscape, increased friction reduces its speed. The result is a pileup of air (convergence). When air converges, there is an upward flow of air molecules rather than a simple squeezing together of molecules (as happens when people enter a crowded building).

Convergence is the horizontal inflow of air that results in vertical lifting of air and cloudy conditions.

Eye on the Atmosphere 4.2

When viewed from space, the most striking feature of our planet is *water*. It is found as a liquid in the global oceans, as a solid in the polar ice caps, and as clouds and water vapor in the atmosphere. Although only one-thousandth of 1 percent of the water on Earth exists as water vapor, it has a huge influence on our planet's weather and climate.



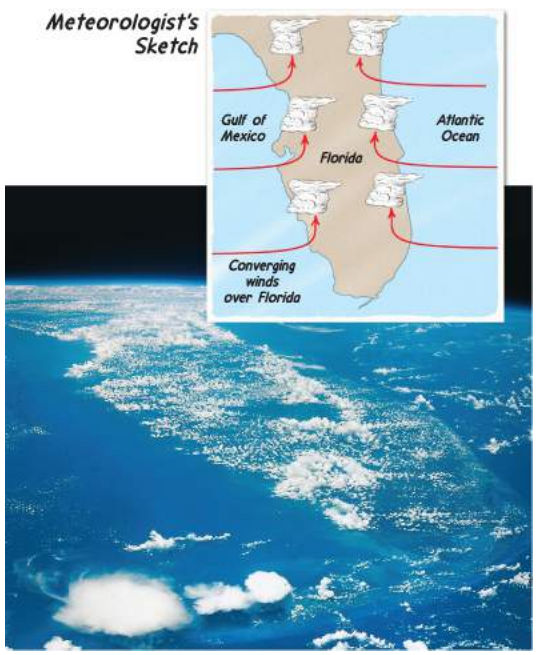
Apply What You Know

1. What role does water vapor play in heating Earth's surface?
2. How does water vapor act to transfer heat from Earth's land–sea surface to the atmosphere?

The Florida peninsula provides an excellent example of the influence of convergence in cloud development and precipitation. On warm days, air flows from the ocean toward land along both coasts of Florida. This leads to a pileup of air along the coasts and general convergence over the peninsula. This pattern of convergence and uplift is aided by intense solar heating of the land. As a result, Florida's peninsula experiences the greatest frequency of midafternoon thunderstorms in the United States (Figure 4.20).

Smartfigure 4.20 **Convergence over the Florida peninsula**

When surface air converges, the column of air increases in height to allow for the decreased area it occupies. Florida provides a good example. On warm days, airflow from the Atlantic Ocean and Gulf of Mexico onto the Florida peninsula generates many midafternoon thunderstorms.



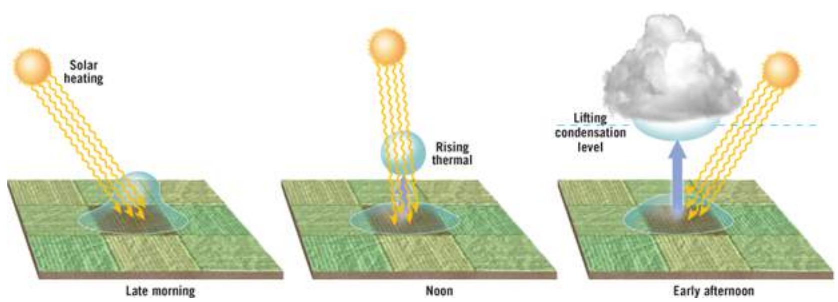
Watch **SmartFigure: Frontal Wedging and Convergence**

Localized Convective Lifting

On warm summer days, unequal heating of Earth's surface may cause pockets of air to be warmed more than the surrounding air (Figure 4.21). For instance, air above a plowed field will be warmed more than the air above adjacent fields of crops. Consequently, the parcel of air above the field, which is warmer (less dense) than the surrounding air, will be buoyed upward. These rising parcels of warmer air are called *thermals*. Birds such as hawks and eagles use thermals to carry them to great heights, where they can identify unsuspecting prey. Humans have learned to employ these rising parcels to use hang gliders as a way to "fly."

Figure 4.21 Localized convective lifting

Unequal heating of Earth's surface causes pockets of air to be warmed more than the surrounding air. These buoyant parcels of hot air rise, producing thermals, and if they reach the lifting condensation level, clouds form.



> Localized convective lifting is the result of unequal surface heating that causes buoyant pockets of air to rise.

The phenomenon that produces rising thermals is called **localized convective lifting**, or simply **convective lifting**. When these warm parcels of air rise above the lifting condensation level, clouds form and on occasion produce midafternoon rain showers. The height of clouds produced in this fashion is somewhat limited, because the buoyancy caused solely by unequal surface heating is confined to, at most, the first few kilometers of the atmosphere. Also, the accompanying rains, although occasionally heavy, are of short duration and widely scattered.

Concept Checks 4.6

- What is meant by *orographic lifting*?
- How does frontal lifting cause air to rise?
- Define *convergence*. Identify two weather systems associated with convergence in the lower atmosphere.
- Describe convective lifting.

4.7 The Critical Weathermaker: Atmospheric Stability

LO 7 Explain the relationship between environmental lapse rate and stability.

Why do clouds vary so much in size and shape, and why does the resulting precipitation vary so widely? The answer is closely tied to the *stability* of the air. Recall that when a parcel of air is forced to rise, its temperature will decrease because of expansion (adiabatic cooling). By comparing the parcel's temperature to that of the surrounding air, we can determine its stability. If the parcel is *cooler* than the surrounding environment, it will be more dense and, if allowed to do so, it will sink to its original position. Air of this type, called **stable air**, resists vertical movement.

If, however, our imaginary rising parcel is *warmer* and hence less dense than the surrounding air, it will continue to rise until it reaches an altitude where its temperature equals that of its surroundings. This type of air is classified as **unstable air**. Unstable air is like a hot-air balloon: It will rise as long as the air in the balloon is sufficiently warmer and less dense than the surrounding air (Figure 4.22).

Figure 4.22 Hot air rises

As long as air is warmer than its surroundings, it will rise. Hot-air balloons rise up through the atmosphere for this reason.

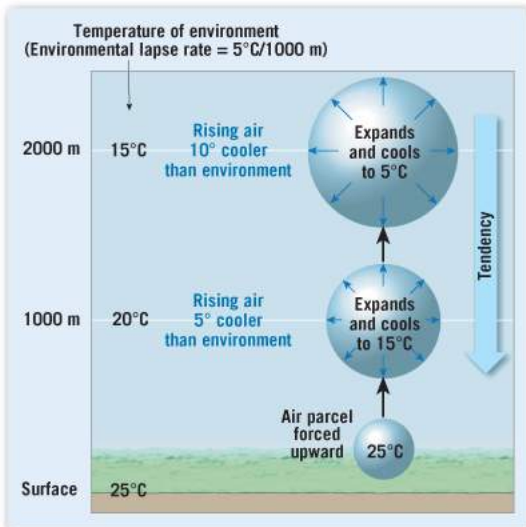
Types of Stability

The stability of the atmosphere is determined by regularly measuring the air temperature at various heights. This measure, called the **environmental lapse rate (ELR)**, should not be confused with adiabatic temperature changes. The environmental lapse rate is rate of change in the *actual temperature* of the atmosphere with height, as determined from observations made by radiosondes and aircraft. (Recall that a radiosonde is an instrument package that is attached to a balloon and transmits data by radio as it ascends though the atmosphere.) Adiabatic temperature changes, by contrast, are the *changes in temperature due to pressure changes* that a parcel of air experiences as it moves vertically through the atmosphere.

Figure 4.23 illustrates how the stability of the atmosphere is determined. Notice that the temperature of the environment at 1000 meters above the surface is 5°C cooler than the air at the surface, whereas the environment at 2000 meters is 10°C cooler, and so forth. Thus, the prevailing environmental lapse rate is 5°C per 1000 meters. The air at the surface appears to be less dense than the air at 1000 meters because it is 5°C warmer. However, if the surface air were forced to rise to 1000 meters, it would expand and cool at the dry adiabatic rate of 10°C per 1000 meters. Therefore, on reaching 1000 meters, the rising parcel would have experienced a drop in temperature from 25°C to 15°C. The temperature of the environment at 1000 meters, on the other hand, is 20°C. Because the rising air would be 5°C cooler than its environment, it would be denser and, if allowed to do so, would sink to its original position. Thus, the air near the surface, depicted in Figure 4.23, will not rise unless forced to do so, and is referred to as *stable*.

Figure 4.23 How the stability of the air is determined

When an unsaturated parcel of air is lifted, it expands and cools at the dry adiabatic rate of 10°C per 1000 meters. In this example, the temperature of the rising parcel of air is lower than that of the surrounding environment; therefore, it will be heavier and, if allowed to do so, will sink to its original position.



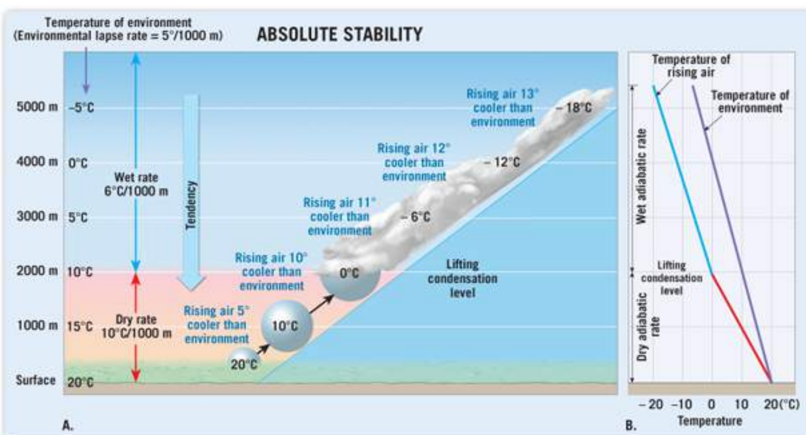
We will now look at three fundamental conditions of the atmosphere: absolute stability, absolute instability, and conditional instability.

Absolute Stability

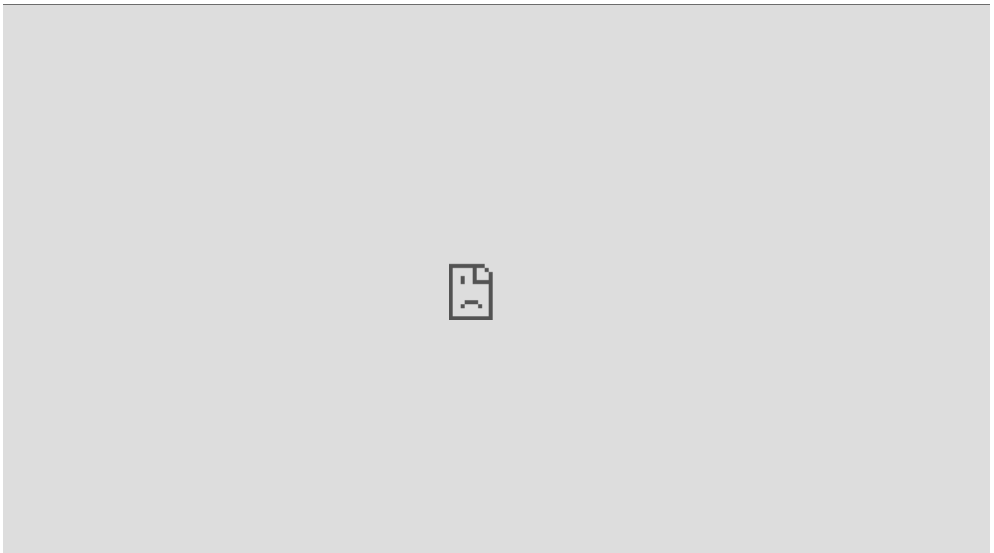
Stated quantitatively, **absolute stability** prevails when *the environmental lapse rate is less than the wet adiabatic rate*. Figure 4.24 depicts this situation by using an environmental lapse rate of 5°C per 1000 meters (and a wet adiabatic rate of 6°C per 1000 meters). Note that at 1000 meters, the temperature of the rising parcel is 5°C cooler than its environment, which makes it denser. Even if this stable air were forced above the lifting condensation level, it would remain cooler and denser than its environment and would have a tendency to return to the surface.

Smartfigure 4.24 **Atmospheric conditions that result in absolute stability**

Absolute stability prevails when the environmental lapse rate is less than the wet adiabatic rate. **A.** The rising parcel of air is always cooler and heavier than the surrounding air, producing stability. **B.** Graphical representation of the conditions shown in part **A.**



Watch **SmartFigure: Atmospheric Stability**



Despite its tendency to remain near Earth's surface, stable air can be forced aloft, most commonly by frontal lifting. If stable air is forced above the lifting condensation level, flat widespread clouds will be generated. Precipitation, if any, will be light to moderate, depending on the moisture content of the air. Dreary, overcast days with periodic light rain throughout the day are likely when stable air is forced to rise.

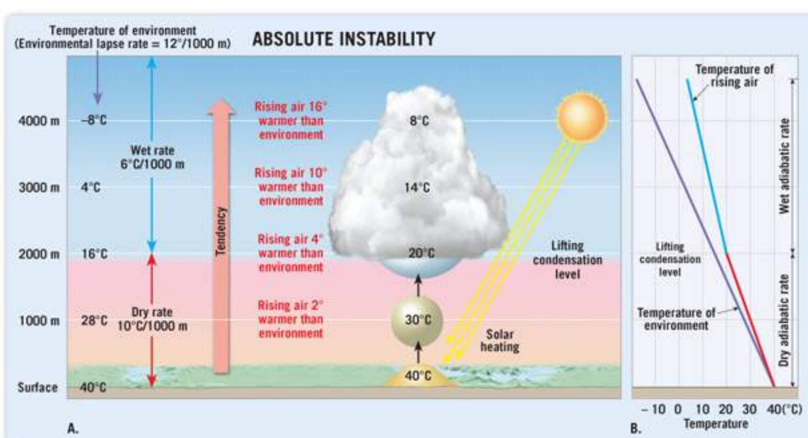
> When moist air has an environmental lapse rate *between the dry and wet adiabatic rates*, it exhibits conditional instability and, if forced aloft, has the potential to become unstable and produce severe weather.

Absolute Instability

At the other extreme, a layer of air is said to exhibit **absolute instability** when *the environmental lapse rate is greater than the dry adiabatic rate*. As shown in Figure 4.25, the ascending parcel of air is always warmer and less dense than its environment and will continue to rise because of its own buoyancy. Absolute instability occurs most often during the warmest months and on clear days, when solar heating is intense. Under these conditions, the lowermost layer of the atmosphere is heated to a much higher temperature than the air aloft. This results in a steep environmental lapse rate—in other words, environment temperature rapidly decreases with height—and an unstable atmosphere. Convective lifting of the air near Earth's surface generates towering clouds and the potential for midafternoon thunderstorms that tend to dissipate after sunset.

Figure 4.25 Atmospheric conditions that result in absolute instability

A. Absolute instability can develop when solar heating causes the lowermost layer of the atmosphere to be warmed to a much higher temperature than the air aloft. The result is a steep environmental lapse rate that renders the atmosphere unstable. **B.** Graphical representation of the conditions shown in part **A.**



> When the environmental lapse rate is *less* than the wet adiabatic rate, air exhibits absolute stability and resists vertical movement.

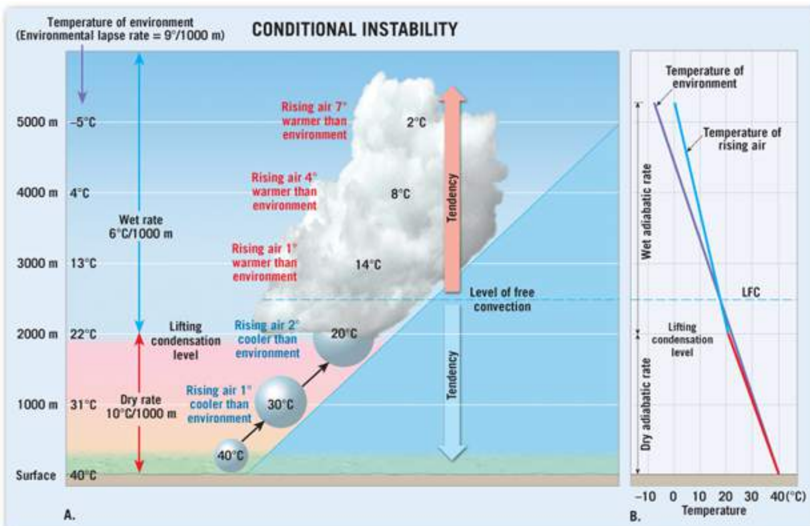
Conditional Instability

A common type of atmospheric instability is called **conditional instability**. This situation prevails when *moist air has an environmental lapse rate between the dry and wet adiabatic rates* (between about 5° and 10°C per 1000 meters). Simply stated, the atmosphere is said to be conditionally unstable when it is *stable* with respect to an *unsaturated* parcel of air but *unstable* with respect to a *saturated* parcel of air.

Notice in Figure 4.26 that the rising parcel of air is cooler than the surrounding air for about 2500 meters. However, because of the release of latent heat that occurs above the lifting condensation level, the parcel eventually becomes warmer than the surrounding air. From this point along its ascent, the parcel will continue to rise without an external force. Keep in mind that conditionally unstable air must be forced upward until it reaches the level where it becomes unstable and rises on its own. The altitude at which air rises because of its own buoyancy is called the **level of free convection (LFC)**.

Figure 4.26 Atmospheric conditions that result in conditional instability

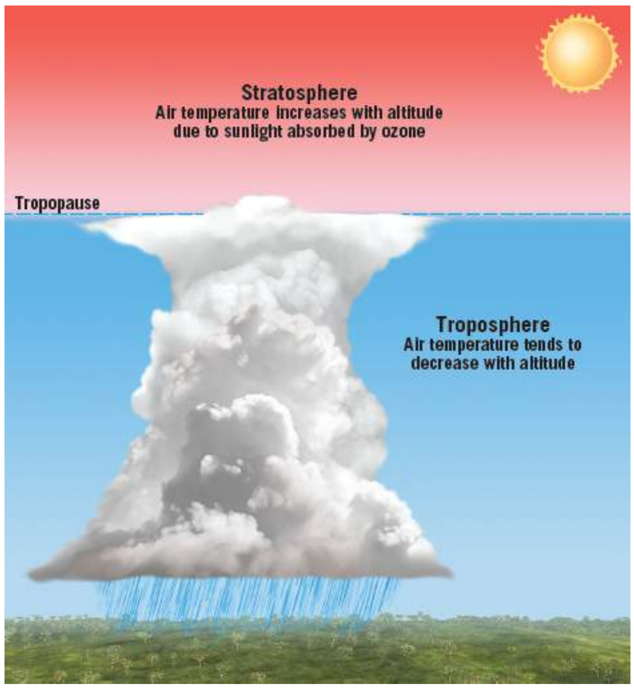
Conditional instability may result when warm air is forced to rise along a frontal boundary. Note that the environmental lapse rate of 9°C per 1000 meters lies between the dry and wet adiabatic rates. **A.** The parcel of air is cooler than the surrounding air up to nearly 2500 meters, where its tendency is to sink toward the surface (stable). Above this level, however, the parcel is warmer than its environment and will rise because of its own buoyancy (unstable). Thus, when conditionally unstable air is forced to rise, the result can be towering cumulus clouds. **B.** Graphical representation of the conditions shown in part **A.**



Conditional instability is usually a summertime phenomenon associated with warm, humid air. When conditionally unstable air is lifted above the lifting condensation level, the result is usually towering thunderstorms. However, clouds do not continue to grow indefinitely (Figure 4.27). The massive clouds associated with thunderstorms, for example, can rise for several thousand meters, but eventually the rising parcels of air within them reach the base of stratosphere (tropopause). Recall from Chapter 1 that the stratosphere is a **temperature inversion**—a layer of air in which the temperature increases with altitude. When these rising parcels reach the stratosphere, they are cooler than the surrounding environment and lose their buoyancy. Thus, this temperature inversion inhibits further vertical movement and causes the cloud tops to flatten (Figure 4.27).

Figure 4.27 Temperature inversions aloft tend to inhibit cloud growth

In this example, the stratosphere forms a warm inversion layer (caused by solar heating of ozone) and therefore serves as a lid to stop the growth of towering clouds.



> When the environmental lapse rate is *greater* than the dry adiabatic rate, air exhibits absolute instability and will rise because of its buoyancy; it may also produce severe weather.

The level where the rising parcel becomes colder than the environment is called the **equilibrium level (EL)** and is illustrated on a simplified *Stuve diagram* in Box 4.3. In strong thunderstorms, part of the cloud may *overshoot* the equilibrium level because of the strength of the updraft. The result is a dome-shaped structure that protrudes above an otherwise flat cloud top (see Figure 4.27).

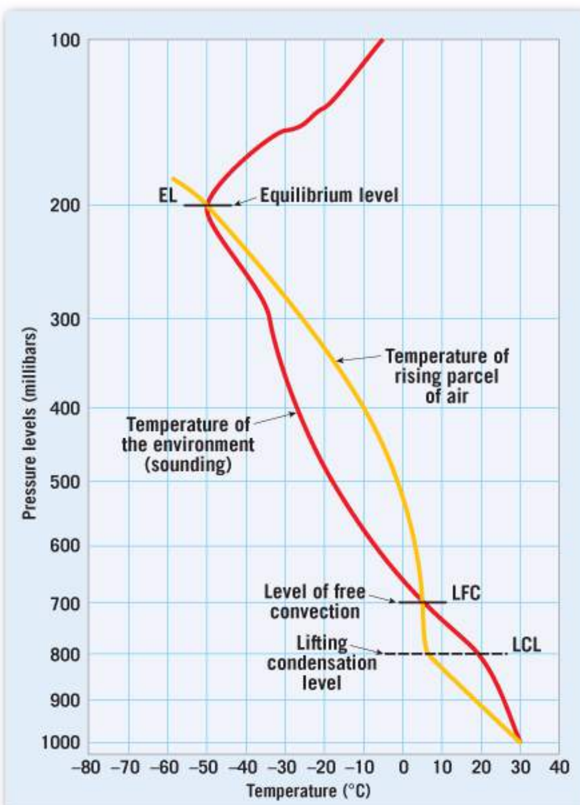
Box 4.3

Exploring Temperatures on a Stuve Diagram

Meteorologists display and analyze upper-air data collected by radiosondes, termed *soundings*, on graphs called *thermodynamic diagrams*. These graphs provide a vertical profile of the temperature and other data up through the atmosphere for a particular time and location. Figure 4.C shows one type of thermodynamic diagram, called a *Stuve diagram.* On the simplified Stuve diagram in Figure 4.C, the horizontal blue lines represent pressure levels in millibars (mb) along the left, while the vertical blue lines indicate temperature in Celsius.

Figure 4.C

Simplified Stuve diagram showing pressure and temperature sounding.



The sounding shown in this Stuve diagram provides actual air temperatures (solid red line) recorded by a radiosonde carried aloft. The yellow line represents the temperature of a rising parcel of air. Notice that at about the 800-millibar level, the yellow line intersects the *lifting condensation level*—the height at which condensation and cloud formation begin—marked on the diagram as LCL. Above the LCL, the yellow line changes direction because the rising parcel is cooling at the lower wet adiabatic rate for saturated air. At about the 700-millibar level, the yellow curve intersects the environmental temperature curve shown by the red line. Therefore, above the 700-millibar level, the rising air is now warmer (less dense) than the temperature of the surrounding air (environment), causing it to become unstable and rise because of its own buoyancy. This level is called the *level of free convection* (LFC).

The region of instability and free convection exists until the yellow line representing the temperature of the rising air once again intersects the sounding temperature (red line) at about the 200-millibar level. At this pressure, the temperature of the rising parcel is again equal to that of its surroundings, causing the parcel to lose buoyancy. This level is called the *equilibrium level* (EL) and is theoretically the top of a growing thunderstorm.

Apply What You Know

1. Explain why an air parcel cools at the wet adiabatic rate above the LCL.
2. What layer of the atmosphere is located above the 200-millibar level?

Concept Checks 4.7

- How does stable air differ from unstable air?
- How is the stability of air determined?
- Describe conditional instability.

4.8 Stability and Daily Weather

LO 8 List the primary factors that influence the stability of air.

How does air stability manifest itself in our daily weather? When stable air is forced aloft, relatively thin widespread clouds typically form, and any precipitation that results is light to moderate. In contrast, as unstable air rises, towering clouds are generated that are usually accompanied by heavy precipitation.

How Stability Changes

Any factor that causes air near the surface to become warmed relative to the air aloft makes air more unstable (increases instability), whereas any factor that causes the surface air to be chilled increases stability. Stated another way, any factor that increases the environmental lapse rate renders the air less stable, whereas any factor that reduces the environmental lapse rate increases the air's stability.

Instability is enhanced by the following:

- Warming of the lowermost layer of the atmosphere by solar radiation during daylight hours
- Heating of a cold air mass from below as it passes over a warm surface or bringing in warm air near the surface (warm air advection)
- Upward movement of air caused by processes such as orographic lifting, frontal lifting, or convergence
- Radiation cooling of cloud tops

Stability is enhanced by the following:

- Radiation cooling of Earth's surface after sunset
- The cooling of an air mass from below as it traverses a cold surface or the arrival of cold surface air (cold air advection)
- Subsidence within an air column

Note that most processes that alter stability result from temperature changes caused by horizontal or vertical air movement, although daily temperature changes are important as well.

Solar Heating and Stability

On clear summer days, when there is abundant surface heating, the lower atmosphere may become warmed sufficiently to cause parcels of air to rise—localized convection. After the Sun sets, surface cooling generally renders the atmosphere stable again.

Horizontal Air Movement and Stability

Changes in stability may occur as air moves horizontally over surfaces that have markedly different temperatures. For example, in the winter, when warm air from the Gulf of Mexico moves northward over the cold, snow-covered Midwest, the air is cooled from below. This *increases the stability* of the air and often produces widespread fog but no cloud development.

On the other hand, *instability* can be enhanced in the winter when frigid polar air moves southward over the open waters of the Great Lakes. Although the Great Lakes are cold in the winter, they are as much as 25°C warmer than a subfreezing polar air mass as it pushes southward across the lakes. During its journey, moisture and heat are added to the frigid polar air from the comparatively warm water below, rendering the air humid and unstable. The result can be heavy snowfalls on the downwind shores of the Great Lakes—called "lake-effect snow."

> Stability is enhanced by either cooling the lower atmosphere or warming the upper atmosphere, whereas instability is enhanced by warming the lower atmosphere or cooling the upper atmosphere.

Vertical Air Movement and Stability

When there is a general downward flow of air, called **subsidence**, the upper part of the air column is heated by compression, more so than the air below. (Usually, the air just above Earth's surface is not involved in subsidence because the ground inhibits sinking motion, so its temperature remains unchanged.) Because the air aloft is warmed more than the air near the surface, subsidence tends to stabilize the atmosphere. Subsidence can occur for different reasons, including the downward motion of a convection cell or air descending the leeward side of a mountain range (Box 4.4). The warming effect of a few hundred meters of subsidence is enough to evaporate clouds. Thus, one sign of subsiding air is a deep blue, cloudless sky.

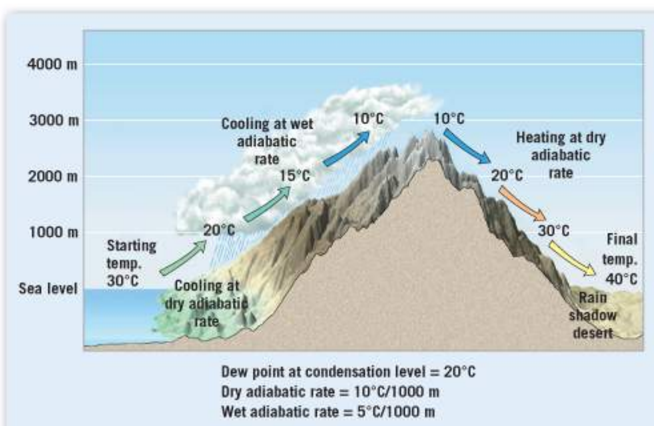
Box 4.4

Orographic Effects: Windward Precipitation and Leeward Rain Shadows

Orographic lifting is a significant factor in the development of windward precipitation and leeward rain shadows. A simplified hypothetical situation, illustrated in Figure 4.D, shows prevailing winds forcing warm moist air over a nearly 3000-meter-high mountain range. As the unsaturated air ascends the windward side of the range, it cools at a rate of 10°C per 1000 meters (dry adiabatic rate) until it reaches the dew-point temperature of 20°C. Because the dew-point temperature is reached at 1000 meters, we can say that this height represents the lifting condensation level and the height of the cloud base. Notice that above the lifting condensation level, latent heat is released, which results in a slower rate of cooling, the wet adiabatic rate.

Figure 4.D

Orographic lifting and the formation of rain shadow deserts.



From the cloud base to the top of the mountain, water vapor within the rising air condenses to form more and more cloud droplets. As a result, the windward side of the mountain range experiences abundant precipitation.

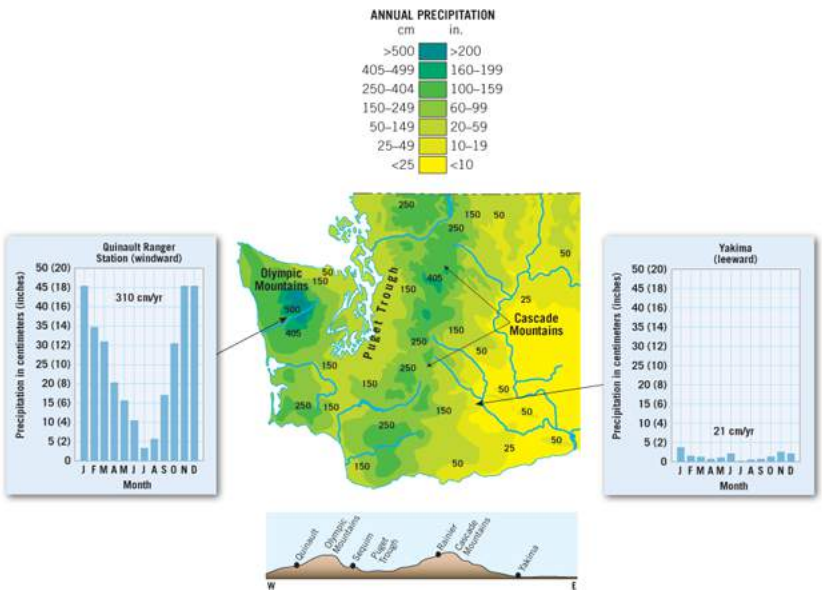
For simplicity, we will assume that the air that was forced to the top of the mountain is cooler than the surrounding air and hence begins to flow down the leeward slope of the mountain. As the air descends, it is compressed and *heated* at the dry adiabatic rate. As the descending air reaches the base of the mountain range, its temperature has risen to 40°C, or 10°C warmer than the temperature at the base of the mountain on the windward side. The higher temperature on the leeward side is a result of the latent heat that was released during condensation as the air ascended the windward slope of the mountain range.

Two factors account for the rain shadow commonly observed on leeward mountain slopes. First, water is extracted from air in the form of precipitation on the windward side. Second, the air on the leeward side is warmer than the air on the windward side. (Recall that an increase in temperature results in a drop in relative humidity.)

A classic example of windward precipitation and leeward rain shadows is found in western Washington State. As moist Pacific air flows inland over the Olympic and Cascade Mountains, orographic precipitation is abundant (Figure 4.E). By contrast, precipitation data for Yakima indicates the presence of a rain shadow on the leeward side of these highlands.

Figure 4.E

Distribution of precipitation in western Washington State.



Apply What You Know

1. Give two reasons why the air on the windward side of a topographic barrier has a higher relative humidity than when it arrives on the leeward side.

Upward movement of air generally enhances *instability* and is particularly significant in generating towering clouds and thunderstorms during the warm summer months. Recall that when *conditionally unstable air* is forcefully lifted along a front, it can become *unstable* and continue to rise because of its buoyancy (see Figure 4.26). This can also occur when warm moist air is forced up a mountain, leading to dangerous thunderstorms, which may cause flash flooding in the adjacent valleys.

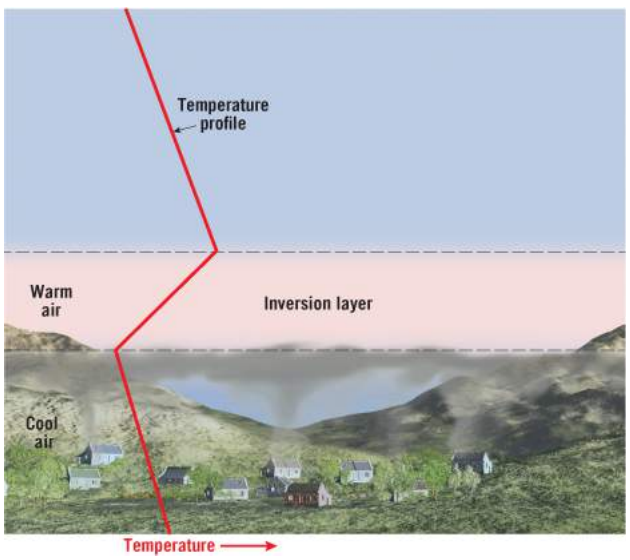
Radiation Cooling from Clouds

The loss of heat by radiation emitted from cloud tops during evening hours adds to their instability and growth. Unlike air, which is a poor radiator of heat, cloud droplets emit considerable energy to space. Towering clouds that owe their growth to surface heating lose that source of energy at sunset. After sunset, however, radiation cooling at their tops steepens the lapse rate near the tops of these clouds and can lead to additional upward flow of warmer air below. This process is responsible for producing nocturnal thunderstorms from clouds whose growth temporarily ceased around sunset.

Temperature Inversions and Stability

The most stable atmospheric conditions are associated with temperature inversions. Recall that a *temperature inversion* is a layer in which the temperature increases with altitude rather than the more common condition of decreasing with altitude (Figure 4.28). This phenomenon can occur within any layer of the atmosphere. Temperature inversions act like a lid that keeps rising air from penetrating the inversion. There are two main types of inversions—those that occur near the surface and those that develop aloft.

Figure 4.28 Temperature profile typical of a low-level temperature inversion



Many processes can generate a temperature inversion, such as radiation cooling of Earth's surface on a clear night. After sunset, Earth's surface loses energy quickly and, through conduction, cools the air near the surface. However, because air is a poor conductor of heat, the air aloft remains comparatively warm.

When the air near the surface is cooler and heavier than a layer of air aloft, minimal vertical mixing occurs between the two layers. Because pollutants are generally added to the atmosphere from below, a temperature inversion confines the pollutants to the lowermost layer, where their concentration will continue to increase until the temperature inversion dissipates (Figure 4.29).

Figure 4.29 Pollution trapped by a temperature inversion

> A temperature inversion is a layer in which temperature increases with altitude, thereby acting like a lid to stop the upward movement of previously buoyant air.

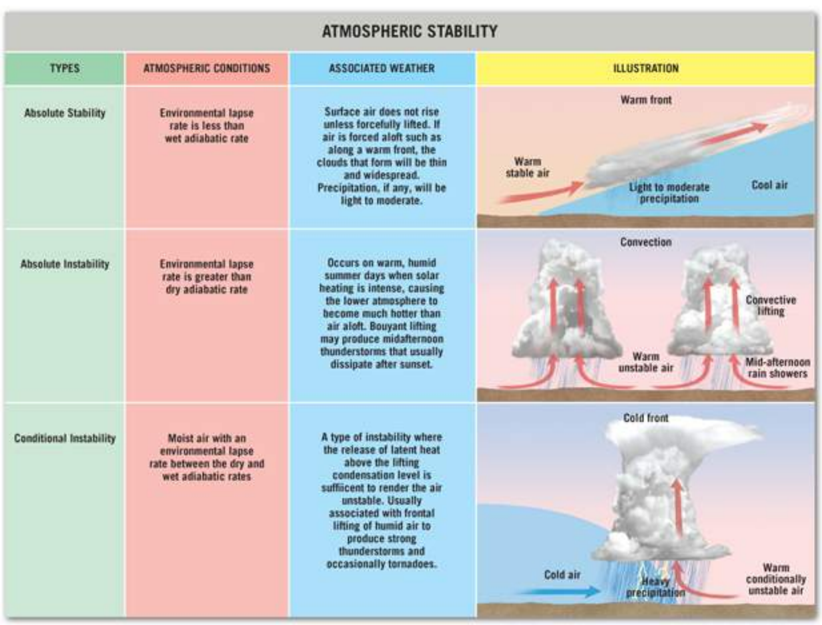
Widespread fog can also be enhanced by a temperature inversion. Fog often forms after sunset because of radiation cooling. If an inversion develops, it inhibits mixing between the moist, fog-laden air near the surface and dryer air aloft—thus preventing the fog from dissipating.

Temperature inversions that occur aloft can cause convective clouds to spread out and take on a flattened appearance. One example is the flattened tops of towering storm clouds that reach the top of the troposphere. This temperature inversion is the result of solar heating of the ozone layer that is found in the stratosphere (see Figure 4.27).

Subsidence as a mechanism for generating temperature inversions aloft is discussed in Chapter 13.

The role of stability in determining our daily weather is summarized in Figure 4.30. The air’s stability, or lack of it, determines to a large degree whether clouds develop and produce precipitation and whether that precipitation will come as a gentle shower or a violent downpour. When stable air is forced aloft, the associated clouds generally have little vertical thickness, and precipitation, if any, is light. In contrast, unstable air can result in towering clouds frequently accompanied by thunderstorms and heavy precipitation. The most stable conditions occur during a temperature inversion, when the air temperature increases with height and inhibits vertical air movement.

Figure 4.30 Comparison of the three types of atmospheric stability



Concept Checks 4.8

- What weather conditions would lead you to believe that air is unstable? Stable?
- List four ways instability can be enhanced.
- List three ways stability can be enhanced.

Concepts in Review

4.1 Water on Earth

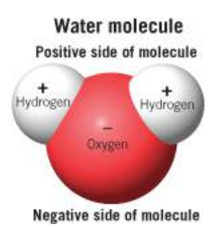
LO 1 Describe the movement of water through the hydrologic cycle. List and describe water's unique properties.

Key Terms

hydrologic cycle

hydrogen bonds

- The unending circulation of Earth's water supply is called the hydrologic cycle.
- Water has unique properties: (1) It is the only liquid found at Earth's surface in large quantities; (2) it is readily converted from one state of matter to another (solid, liquid, gas); (3) its solid phase, ice, is less dense than liquid water; and (4) it has a high heat capacity—meaning it requires considerable energy to change its temperature.



4.2 Water's Changes of State

LO 2 Summarize the six processes by which water changes from one state of matter to another. For each, indicate whether energy is absorbed from or released to the environment.

Key Terms

calorie

latent heat

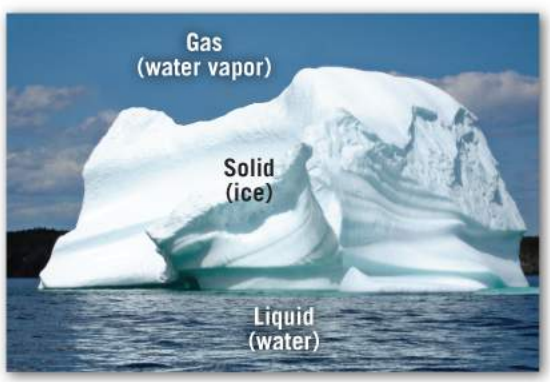
evaporation

condensation

sublimation

deposition

- Water can change from one state of matter (solid, liquid, or gas) to another at the temperatures and pressures experienced on Earth.
- The processes involved in changes of state include evaporation, condensation, melting, freezing, sublimation, and deposition. During each change, latent (hidden, or stored) heat is either absorbed or released.



4.3 Humidity: Water Vapor in the Air

LO 3 Explain the relationship between air temperature and the amount of water vapor needed to saturate air.

Key Terms

humidity

absolute humidity

mixing ratio

vapor pressure

saturation

saturation vapor pressure

- Humidity is the general term used to describe the amount of water vapor in the air. The methods used to quantitatively express humidity include (1) absolute humidity, (2) mixing ratio, (3) vapor pressure, (4) relative humidity, and (5) dew point.
- When air is saturated, the pressure exerted by the water vapor, called the saturation vapor pressure, produces a balance between the number of water molecules leaving the surface of the water and the number returning.

4.4 Relative Humidity and Dew-Point Temperature

LO 4 List and describe the ways relative humidity changes in nature. Compare relative humidity to dew-point temperature.

Key Terms

relative humidity

dew-point temperature (dew point)

hygrometer

psychrometer

- Relative humidity can change in two ways: (1) when the amount of moisture in the air increases or decreases or, (2) when the temperature of the air rises or falls.
- The dew-point temperature (or simply, dew point) is the temperature to which a parcel of air must be cooled to the point of condensation.
- A variety of instruments called hygrometers are used to measure relative humidity.

4.5 Adiabatic Temperature Changes and Cloud Formation

LO 5 Describe adiabatic temperature changes and explain why the wet adiabatic rate of cooling is less than the dry adiabatic rate.

Key Terms

adiabatic temperature change

parcel

dry adiabatic rate

lifting condensation level (LCL)

wet adiabatic rate

- When air expands, it cools, and when air is compressed, it warms. Temperature changes produced by means of changes in air pressure, in which thermal energy is neither added nor subtracted, are called adiabatic temperature changes.
- When air rises, it expands and cools adiabatically. If air is lifted sufficiently, it will cool to its dew-point temperature, and clouds will develop.

4.6 Processes That Lift Air

LO 6 Identify four mechanisms that cause air to rise.

Key Terms

orographic lifting

rain shadow desert

front

frontal lifting (frontal wedging)

convergence

localized convective lifting (convective lifting)

- Four mechanisms that cause air to rise are (1) orographic lifting, (2) frontal lifting, (3) convergence, and (4) localized convective lifting.

4.7 The Critical Weathermaker: Atmospheric Stability

LO 7 Explain the relationship between environmental lapse rate and stability.

Key Terms

stable air,

unstable air

environmental lapse rate (ELR)

absolute stability

absolute instability

conditional instability

level of free convection (LFC)

temperature inversion

equilibrium level (EL)

- Stable air resists vertical movement, whereas unstable air rises because of its buoyancy.
- The three fundamental conditions of the atmosphere are (1) absolute stability, (2) absolute instability, and (3) conditional instability.
- In general, when stable air is forced aloft, the associated clouds cover most of the sky and produce light to moderate precipitation that may continue all day. In contrast, clouds associated with unstable air are towering and frequently accompanied by heavy rain.

4.8 Stability and Daily Weather

LO 8 List the primary factors that influence the stability of air.

Key Terms

subsidence

- Any factor that causes air near the surface to become warmed in relation to the air aloft increases the air's instability. The opposite is also true: Any factor that causes the surface air to be chilled compared to air aloft results in the air becoming more stable.
- The most stable atmospheric conditions are associated with temperature inversions.

Exercises and Online Activities

Mastering Meteorology™

For instructor-assigned homework, test prep resources, and other learning materials, visit **Mastering Meteorology.**

Review Questions

Answering the following questions will help you review for this chapter.

1. Sketch and label the main components of the hydrologic cycle.
2. Describe hydrogen bonds and how they relate to water's properties.
3. What is latent heat, and why is it important in water's phase changes?
4. Define *evaporation*, *condensation*, *freezing*, *melting*, *deposition*, and *sublimation*.
5. What is absolute humidity? Mixing ratio? Vapor pressure?
6. Define *saturation*, and explain what is meant by saturation vapor pressure.
7. List the ways relative humidity can change in nature.
8. What does the dew-point temperature tell us about the moisture content of the air?
9. Which has a greater capacity to hold water vapor molecules, warm air or cold air?
10. How does a hygrometer work?
11. Describe what is meant by an adiabatic temperature change.
12. What is the dry adiabatic rate? Wet adiabatic rate? Which is greater, and why?
13. Distinguish among the lifting condensation level (LCL), level of free convection (LFC), and equilibrium level (EL).
14. List and describe four mechanisms that cause air to rise to form clouds.
15. Define *rain shadow*.
16. What is absolute stability? Absolute instability? Conditional instability?
17. What is the difference between the environmental lapse rate and the adiabatic lapse rate?

18. List the mechanisms that cause air to become more stable, as well as those that cause air to become less stable.

19. Explain the role that stability plays in daily weather.

Give It Some Thought

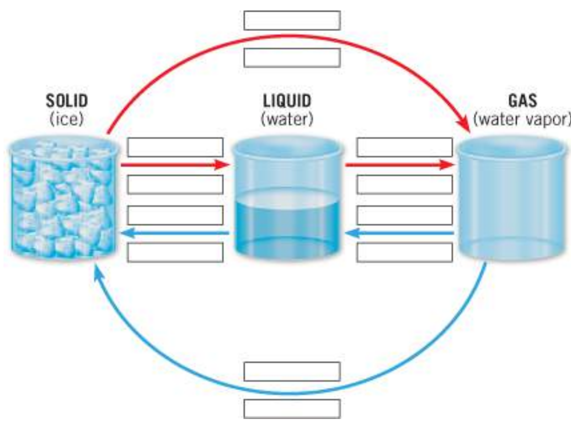
1. Refer to Figure 4.3 to complete the following.

  a. In which state of matter is water the most dense?

  b. In which state of matter are water molecules most energetic?

  c. In which state of matter is water compressible?

2. In the boxes above each arrow, label the diagram with the appropriate terms for the changes in state that are shown. Below each arrow, indicate whether latent heat is absorbed from or released to the environment.



3. The accompanying photo shows a cup of hot coffee. In what state of matter is the "steam" rising from the liquid? (*Hint:* Can you see water vapor?)

4. The primary mechanism by which the human body cools itself is perspiration.

a. Explain how perspiring cools the skin.

b. Referring to the data for Phoenix, Arizona, and Tampa, Florida (Table A), in which city would it be easier to stay cool by perspiring? Explain your choice.

TABLE A

City	Temperature	Dew point temperature
Phoenix, AZ	101°F	47°F
Tampa, FL	101°F	77°F

5. As shown in the accompanying photo, during hot summer weather, many people put "koozies" around their beverages to keep drinks cold. Describe at least two ways the koozies help keep beverages cold.

6. Refer to Table 4.1 to answer this question. How much more water is contained in saturated air at a tropical location with a temperature of 40°C compared to a polar location with a temperature of –10°C?

7. Refer to the data for Phoenix, Arizona, and Bismarck, North Dakota (Table B), to complete the following:

a. Which city has a higher relative humidity?

b. Which city has the greatest quantity of water vapor in the air?

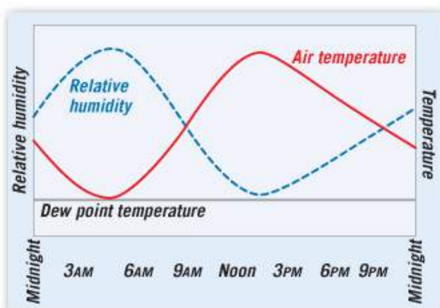
c. In which city is the air closest to its saturation point with respect to water vapor?

d. In which city does the air have the greatest holding capacity for water vapor?

TABLE B

City	Temperature	Dew point temperature
Phoenix, AZ	101°F	47°F
Bismark, ND	39°F	38°F

8. Are the atmospheric conditions illustrated in Figure 4.21 an example of absolute stability, absolute instability, or conditional instability?
9. The accompanying graph shows how air temperature and relative humidity change on a typical summer day in the Midwest.
   - **a.** Assuming that the dew-point temperature remained constant, what would be the best time of day to water a lawn to minimize evaporation of the water sprayed on the grass?
   - **b.** Use this graph to explain why dew almost always forms early in the morning.



10. This chapter examines four processes that cause air to rise. Describe how convective lifting is different from the other three processes.

By the Numbers

1. Using Table 4.1, answer the following:
    - a. If a parcel of air at 25°C contains 10 grams of water vapor per kilogram of air, what is its relative humidity?
    - b. If a parcel of air at 35°C contains 5 grams of water vapor per kilogram of air, what is its relative humidity?
    - c. If a parcel of air at 15°C contains 5 grams of water vapor per kilogram of air, what is its relative humidity?
    - d. If the temperature of the parcel of air in part c dropped to 5°C, how would its relative humidity change?
    - e. If 20°C air contains 7 grams of water vapor per kilogram of air, what is its dew point?
2. If you were to start with a 1-gallon pot of water having a temperature of 10°C and boil it away completely on a stove, it would take a considerable amount of time. Large amounts of energy from the burner would have to be conducted into the pot of water to bring it up to its boiling temperature (100°C), and even more energy would be required to convert it to a gas. If you could take all the vaporized water that you boiled away and instantly condensed it back into the pot, it would release enough energy to blow your house off its foundation. Do the calculation to prove that this statement is true.

    Important information:

    1 gallon of water = 3785 grams

    J = Joule, a unit of energy used in the SI system

    4.186 J/g = amount of energy required to raise 1 gram of water 1°C

    2260 J/g = energy required to vaporize 1 gram of liquid water when the water's temperature is 100°C

    10°C = starting temperature of water

    2.1×10^6 J = amount of energy contained in one stick of dynamite

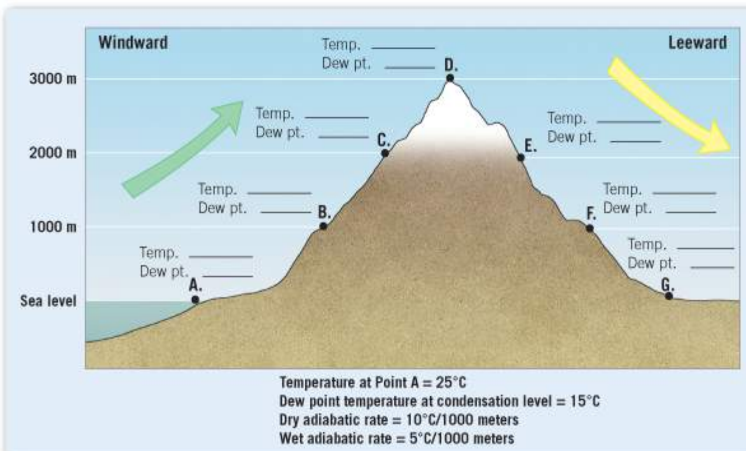
How much energy (measured in sticks of dynamite) is needed to completely boil away 1 gallon of water? This is the same amount of energy that would be released if the water vapor condensed back into the pot.

3. Using the standard tables (Appendix C, Tables C-1 and C-2), determine the relative humidity and dew-point temperature if the dry-bulb thermometer reads 22°C and the wet-bulb thermometer reads 16°C. How would the relative humidity and dew point change if the wet-bulb reading were 19°C?
4. If unsaturated air at 20°C were to rise, what would its temperature be at a height of 500 meters? If the dew-point temperature at the lifting condensation level were 11°C, at what elevation would clouds begin to form?
5. Fill out the accompanying diagram to answer the following. (*Hint:* Read Box 4.4.)
    - **a.** What is the elevation of the cloud base?
    - **b.** What is the temperature of the ascending air when it reaches the top of the mountain?
    - **c.** What is the dew-point temperature of the rising air at the top of the mountain? (Assume 100 percent relative humidity.)
    - **d.** Estimate the amount of water vapor that must have condensed (in grams per kilogram) as the air moved from the cloud base to the top of the mountain.
    - **e.** What will the temperature of the air be if it descends to point G? (Assume that the moisture that condensed fell as precipitation on the windward side of the mountain.)
    - **f.** What is the approximate capacity of the air to hold water vapor at point G?
    - **g.** Assuming that no moisture was added or subtracted from the air as it traveled downslope, estimate the relative humidity at point G.

h. What is the *approximate* relative humidity at point A? (Use the dew-point temperature at the lifting condensation level for the surface dew point.)

i. Give two reasons for the difference in relative humidity between points A and G.

j. Needles, California, is situated on the dry leeward side of a mountain range similar to the position of point G. What term describes this situation?



6. Figure 4.8 shows the nonlinear relationship between air temperature and the saturation mixing ratio. This relationship makes it possible for two unsaturated air parcels to mix and form a saturated parcel. For example, consider the following two parcels of air:

	A	B
Temperature	10°C	40°C
Relative humidity	75%	85%

a. Use Table 4.1 to find the *saturation mixing ratios* of parcels A and B.

b. What are the actual mixing ratios of Parcels A and B?

Answer parts c–g, assuming that the two air masses mix together and the resulting temperature is halfway between 10°C and 40°C, and the actual mixing ratio is halfway between the values you found for the two parcels in part b.

c. What is the temperature of the combined parcel? ____________ °C

d. What is the saturation mixing ratio of the combined parcel? ____________ g/kg

e. What is the actual mixing ratio of the combined parcel? ____________ g/kg

f. How much does the actual mixing ratio differ from the saturation mixing ratio? ____________ g/kg

g. Because relative humidity normally does not exceed 100 percent, what must happen to the excess water vapor in the combined parcel?

h. Describe a situation in which the mixing of two unsaturated parcels of air produces a parcel of saturated air.

7. Calculate the lifting condensation level (LCL) for the two following examples. (Assume that the dew point does not change until after the LCL is reached.)

	Surface Temperature	Surface Dew Point	LCL
Example A	35°C	20°C	___
Example B	35°C	14°C	___

What do these calculations tell you about the relationship between surface dew-point temperature and the height at which clouds develop?

8. Imagine a parcel of air that has a temperature of 40°C at the surface and a dew-point temperature of 20°C at the lifting condensation level. Assume that the environmental lapse rate is 8°C per 1000 meters, the dry adiabatic lapse rate is 10°C per 1000 meters, and the wet adiabatic lapse rate is 6°C/1000 meters. In

Table C, record the environmental temperature, the parcel temperature, and the temperature difference (parcel temperature minus the environmental temperature), and then determine whether the atmosphere is *stable* or *unstable* at each height.

TABLE C				
Height (meters)	Parcel Temperature °C	Environmental Temperature °C	Temperature difference (Parcel-environment	Stable or unstable
7000				
6000				
5000				
4000				
3000				
2000				
1000				
Surface	40°C	40°C	0°C	Stable

a. What is the height of the lifting condensation level?

b. Does this example describe absolute stability, absolute instability, or conditional instability?

c. Would you forecast thunderstorms under these conditions?

Beyond the Textbook

1. Water Vapor Satellite Loop

Water vapor provides the primary fuel for the stormy weather we experience. Watch the water vapor loop from GOES EAST at: http://www.ssec.wisc.edu/data/geo/. Click the button next to "Water Vapor 6.5 μm" under Imager Channel, and then click the button next to "8 Image Animation" under Latest Image/Animation. (*Note*: This is a Flash animation; click on *Java Script* for a non-Flash animation). This satellite video shows how water vapor moves across the middle and eastern United States. Notice that some areas are nearly white, indicating lots of moisture in the air. Others are black, indicating dry air. Notice that most of the moisture that influences the weather in the middle and eastern United States is channeled up from the Gulf of Mexico. You may also see swirls or comma-shaped areas in the moisture field—these are midlatitude cyclones.

1. In what general direction are the areas of moist air flowing across the United States?
2. Describe which lifting mechanisms may be at work in the far Western United States, the Great Plains, and the Gulf Coast states.

2. Temperature, Dew-point Temperature, and Relative Humidity

This activity explores the connection between air temperature, dew-point temperature, and relative humidity. Go to https://digital.weather.gov/ to display the maximum temperatures for today's date. Next, using the dropdown menu button next to Maximum Temperature (°F), select Temperature (°F). Use that map to answer the following:

1. Record the day and month of the year.
2. What is the temperature for the reporting station located nearest to you?
3. What is the temperature for Yuma, Arizona (located in the very southwest corner of Arizona), and Miami, Florida (located near the southeast tip of Florida).

Using the same dropdown menu, select Dew Point (°F) to bring up a new map.

4. Record the dew-point temperature for your location; Yuma, Arizona; and Miami, Florida.

Using the same dropdown menu, select Relative Humidity (%).

5. Using that map, record the relative humidity for your location; Yuma, Arizona; and Miami, Florida.

With the data you have collected, answer the following:

6. Which of these three locations has the greatest difference between the air temperature and dew-point temperature? Which

of the three has the smallest difference between the air temperature and dew-point temperature?

7. Which of these three locations has the highest relative humidity? Lowest relative humidity?

Complete the following statement by inserting the words *smallest* or *largest*.

8. When the relative humidity is the highest, the difference between the air temperature and the dew-point temperature is the ______________, whereas in locations where the relative humidity is the lowest, the difference between the air temperature and the dew-point temperature is the ______________.

Chapter 5 Forms of Condensation and Precipitation

Torrential rain falling at a campsite at Cornbury Music Festival, London.

Focus on Concepts

Each statement represents the primary learning objective for the corresponding major heading within the chapter. After you complete the chapter, you should be able to:

1. Explain the roles of adiabatic cooling and cloud condensation nuclei in cloud formation (5.1).
2. Name and describe the 10 basic cloud types, based on form and height. Contrast nimbostratus and cumulonimbus clouds and their associated weather (5.2).
3. Identify the basic types of fog and describe how each forms (5.3).
4. Describe the Bergeron process and explain how it differs from the collision–coalescence process (5.4).
5. Describe the atmospheric conditions that produce rain, snow, sleet, freezing rain, and hail (5.5).
6. Describe the instruments used to measure precipitation, including the standard rain gauge, snow pillow, and weather radar (5.6).
7. Discuss several ways that humans attempt to modify the weather (5.7).

Clouds, fog, and the various forms of precipitation are among the most observable weather phenomena. The primary focus of this chapter is to provide a basic understanding of each. In addition to learning how clouds are classified and named, you will learn that the formation of an average raindrop involves complex processes requiring water from roughly a million tiny water droplets.

5.1 Cloud Formation

LO 1 Explain the roles of adiabatic cooling and cloud condensation nuclei in cloud formation.

Clouds consist of billions of minute water droplets and/or ice crystals that are suspended above Earth's surface. In addition to being prominent and sometimes spectacular features in the sky, clouds are of continual interest to meteorologists because they provide a visual indication of atmospheric conditions. For condensation to generate clouds, the air must reach saturation, and there must be a surface on which the water vapor can condense to form liquid droplets.

How Does Air Reach Saturation?

Saturation occurs in air aloft in one of two ways. First, cooling air to its dew-point temperature causes saturation, which results in condensation and cloud formation. Recall from Chapter 4 that clouds most often form when air rises and cools to its dew-point temperature by the process of *adiabatic cooling*. When a parcel of air ascends, it passes through regions of successively lower air pressure, causing the parcel to expand and cool adiabatically. At a height called the *lifting condensation level*, the ascending parcel will have cooled to its dew-point temperature, and saturation is reached.

Saturation also occurs when cool, unsaturated air passes over a warm water body and sufficient water vapor is added from below. This process is mainly responsible for the formation of low clouds, particularly those that form over the subtropical oceans.

> Saturation occurs when the air temperature is the same as the dew-point temperature.

The Role of Condensation Nuclei

Another requirement for condensation is that there must be a *surface* on which water vapor can condense. Objects at or near the ground, such as blades of grass, are such surfaces. When condensation occurs aloft, tiny particles known as **cloud condensation nuclei** serve this purpose. Without condensation nuclei, a relative humidity well in excess of 100 percent is necessary to produce cloud droplets. (At very low temperatures —low kinetic energies—water molecules will "stick together" in tiny clusters even in the absence of condensation nuclei.)

> Cloud droplet growth begins on cloud condensation nuclei.

Dust storms, particulates from volcanic eruptions, and pollen from plants are major sources of cloud condensation nuclei. In addition, condensation nuclei are introduced into the atmosphere as by-products of combustion (burning) from such sources as forest fires, automobiles, and coal-burning furnaces.

The most effective particles for condensation aloft are **hygroscopic (water-seeking) nuclei**. Common food items such as crackers and cereals are hygroscopic: When exposed to humid air, they absorb moisture and quickly become stale. Over the ocean, salt particles are released into the atmosphere when sea spray evaporates. Because salt is hygroscopic, water droplets begin to form around sea salt particles at relative humidities less than 100 percent. As a result, the cloud droplets that form on hygroscopic particles such as sea salt are generally much larger than those that grow on **hydrophobic (water-repelling) nuclei**. Although hydrophobic particles are not efficient condensation nuclei, cloud droplets will form on them when the relative humidity reaches 100 percent.

Because cloud condensation nuclei have a wide range of affinities for water, cloud droplets of various sizes often coexist in the same cloud—an important factor for the formation of precipitation.

Growth of Cloud Droplets

Initially, the growth of cloud droplets occurs rapidly. However, the rate of growth slows as the large numbers of competing droplets consume the available water vapor. The result is the formation of a cloud consisting of billions of tiny water droplets—usually having radii of 20 micrometers (μm) or less. These cloud droplets are so minute that they remain suspended in air by the smallest updraft.

Even in very moist air, the growth of cloud droplets by additional condensation is quite slow. Furthermore, the size difference between cloud droplets and raindrops is vast—it takes about 1 million cloud droplets to form a single raindrop. Thus, it is not condensation that is responsible for the formation of raindrops (or ice crystals) large enough to fall to the ground without evaporating. We will investigate the processes that generate precipitation later in this chapter.

Concept Checks 5.1

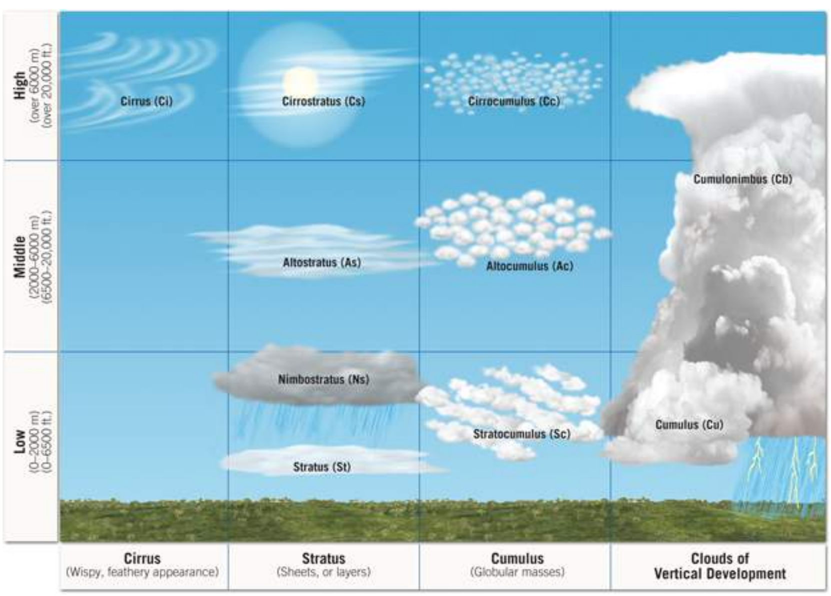
- Describe the process of cloud formation.
- What role do cloud condensation nuclei play in the formation of clouds?
- Why isn’t condensation alone able to generate droplets large enough to fall as rain?

5.2 Cloud Classification

LO 2 Name and describe the 10 basic cloud types, based on form and height. Contrast nimbostratus and cumulonimbus clouds and their associated weather.

In 1803, English naturalist Luke Howard published a cloud classification scheme that serves as the basis of our present-day system. Howard's system classifies clouds on the basis of two criteria: *form* and *height* (Figure 5.1). We will look at the basic cloud forms or shapes first and then examine cloud height.

Smartfigure 5.1 Classification of clouds based on form and height



Watch **SmartFigure: Types of Clouds**

Cloud Forms

Clouds are classified based on how they appear when viewed from Earth's surface. There are three basic forms or shapes:

- ***Cirrus (cirriform)*** clouds are high, white, and thin. They form delicate veil-like patches or wisplike strands and often have a feathery appearance. (*Cirrus* is Latin for "curl" or "filament.")
- ***Cumulus (cumuliform)*** clouds consist of globular cloud masses that look like cotton balls or sheep in the sky. Normally cumulus clouds exhibit a flat base and appear as rising domes or towers. (*Cumulus* means "heap" or "pile" in Latin.) Cumulus clouds form within a layer of the atmosphere where there is some instability leading to convection and rising air.
- ***Stratus (stratiform)*** clouds consist of sheets or layers (*strata*) that cover much or the entire sky. Although there may be minor breaks in the layers, there are no distinct individual cloud units. Stratus clouds form when the atmosphere is stable.

All clouds have at least one of these three basic forms, and some are a combination of two of them; for example, stratocumulus clouds are mostly sheetlike structures composed of long parallel rolls or broken globular patches. In addition, the term **nimbus** (Latin for "violent rain") is used in the name of a cloud that is a major producer of precipitation. Thus, *nimbostratus* denotes a low, relatively flat rain cloud, whereas *cumulonimbus* describes a puffy, tall rain cloud.

> Cloud forms include cirrus (thin or wispy), cumulus (globular masses), and stratus (sheets or layers).

Cloud Height

The second aspect of cloud classification—height—recognizes three levels: high, middle, and low (see Figure 5.1). **High clouds** form in the highest and coldest region of the troposphere and normally have bases above 6000 meters (20,000 feet). Temperatures at these altitudes are usually below freezing, so the high clouds are generally composed of ice crystals or supercooled water droplets. **Middle clouds** occupy heights from 2000 to 6000 meters (6500 to 20,000 feet) and may be composed of water droplets or ice crystals, depending on the time of year and temperature profile of the atmosphere. **Low clouds** form nearer to Earth's surface—up to an altitude of about 2000 meters (6500 feet)—and are generally composed of water droplets, except in winter. These altitudes may vary somewhat depending on season of the year and latitude. For example, at high (poleward) latitudes and during cold winter months, high clouds generally occur at lower altitudes. Further, some clouds extend upward to span more than one height range and are called **clouds of vertical development**.

> Clouds are classified as being high, middle, low, or vertically developed.

The 10 internationally recognized cloud types are summarized in Table 5.1 and described in the sections that follow.

Table 5.1 **Basic Cloud Types**

Cloud Family and Height	Cloud Type	Characteristics
High clouds—above 6000 m (20,000 ft)	Cirrus (Ci)	Thin, delicate, fibrous, ice-crystal clouds. Sometimes appear as hooked filaments called "mares' tails," or cirrus uncinus (Figure 5.2A).
	Cirrocumulus (Cc)	Thin, white, ice-crystal clouds. In the form of ripples or waves, or globular masses all in a row. May produce a "mackerel sky." Least common of high clouds (Figure 5.2B).
	Cirrostratus (Cs)	Thin sheet of white, ice-crystal clouds that may give the sky a milky look. Sometimes produce halos around the Sun and Moon (Figure 5.2C).
Middle clouds—2000–6000 m (6500–20,000 ft)	Altocumulus (Ac)	White to gray clouds, often made up of separate globules; "sheepback" clouds (Figure 5.3A).
	Altostratus (As)	Stratified veil of clouds that is generally thin and may produce very light precipitation. When these clouds are thin, the Sun or Moon may be visible as a "bright spot," but no halos are produced (Figure 5.3B).
Low clouds—below 2000 m (6500 ft)	Stratus (St)	Low uniform layer resembling fog but not resting on the ground. May produce drizzle.
	Stratocumulus (Sc)	Soft, gray clouds in globular patches or rolls. Rolls may join together to make a continuous cloud (Figure 5.4).
	Nimbostratus (Ns)	Amorphous layer of dark gray clouds. One of the primary precipitation-producing clouds (Figure 5.5).
Clouds of vertical development	Cumulus (Cu)	Dense, billowy clouds often characterized by flat bases. May occur as isolated clouds or closely packed (Figure 5.6).
	Cumulonimbus (Cb)	Towering cloud, sometimes spreading out on top to form an "anvil head." Associated with heavy rainfall, thunder, lightning, hail, and tornadoes (Figure 5.7).

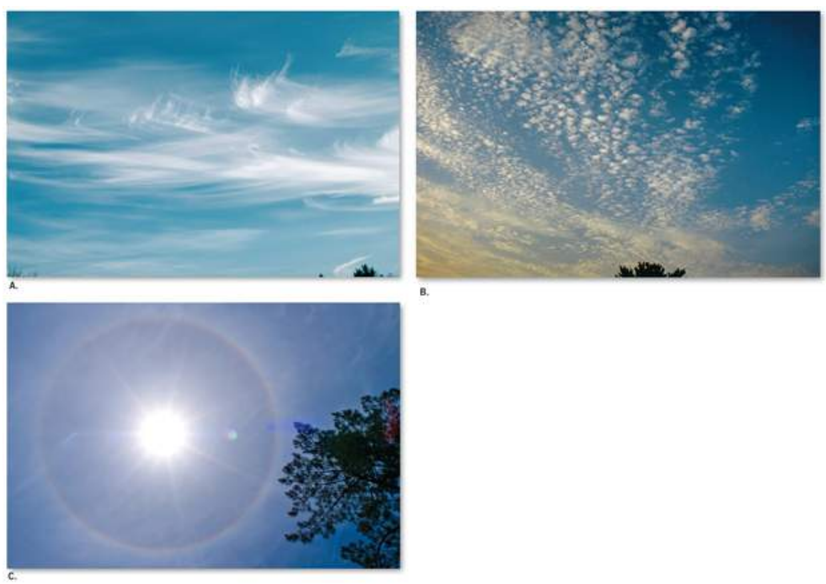
High Clouds

The family of high clouds (above 6000 meters [20,000 feet]) include *cirrus*, *cirrostratus*, and *cirrocumulus*. Low temperatures and small quantities of water vapor present at high altitudes result in high clouds that are thin, white, and made up primarily of ice crystals.

Cirrus (Ci) clouds are composed of delicate, icy filaments. Winds aloft often cause these fibrous ice trails to bend or curl. Cirrus clouds with hooked filaments are called "mares' tails" (Figure 5.2A).

Figure 5.2 Three basic cloud types make up the family of high clouds

A. Cirrus **B.** Cirrocumulus **C.** Cirrostratus.



Cirrocumulus (Cc) clouds appear as white patches composed of small cells or ripples (Figure 5.2B). These small globules, which may be merged or separate, are often arranged in a pattern that resembles fish scales. When this occurs, it is commonly called "mackerel sky."

Although high clouds are not precipitation makers, when cirrus clouds give way to cirrocumulus clouds, they may warn of impending stormy weather. This observation has given rise to an old mariners' phrase: *Mackerel scales and mares' tails make lofty ships carry low sails*.

Cirrostratus (Cs) are transparent, whitish cloud veils with a fibrous or sometimes smooth appearance that may cover much or all of the sky. These clouds are easily recognized when they produce optical effects such as halos around the Sun or Moon (Figure 5.2C). (Optical effects in the atmosphere are discussed in Chapter 16.) Occasionally, cirrostratus clouds are so thin and transparent that they are barely discernible.

Middle Clouds

Clouds that form in the middle altitude range (2000–6000 meters [6500–20,000 feet]) are described with the prefix *alto-* (meaning "middle") and include two types: *altocumulus* and *altostratus*.

Altocumulus (Ac) clouds tend to form in large patches composed of rounded masses or rolls that may or may not merge (Figure 5.3A). Because they are generally composed of water droplets rather than ice crystals, the individual cells usually have a more distinct outline. Altocumulus are sometimes confused with cirrocumulus (which are smaller and less dense) and stratocumulus (which are thicker).

Figure 5.3 Clouds found in the middle-altitude range

A. Altocumulus tend to form in patches composed of rolls or rounded masses. **B.** Altostratus occur as grayish sheets covering a large portion of the sky. When visible, the Sun appears as a bright spot through these clouds.

Altostratus (As) is the name given to a formless layer of grayish clouds that cover all or large portions of the sky. Generally, the Sun is visible through altostratus clouds as a bright spot but with the edge of its disc not discernible (Figure 5.3B). However, unlike cirrostratus clouds, altostratus do not produce halos. Infrequent precipitation in the form of light snow or drizzle may accompany these clouds. Altostratus clouds, which are commonly associated with approaching warm fronts, may thicken into a dark gray layer of nimbostratus clouds capable of producing steady, continuous rain or snow.

Low Clouds

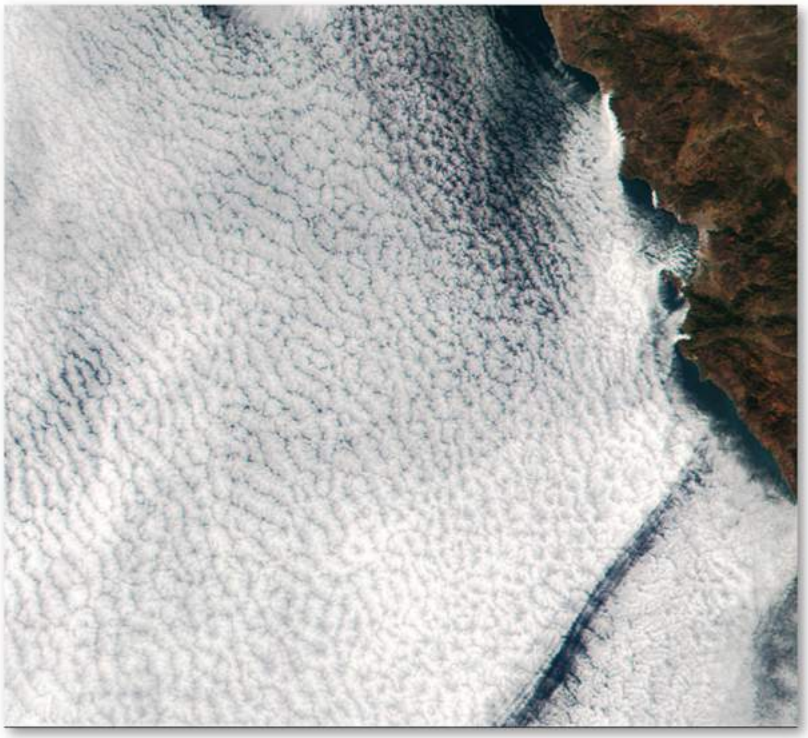
There are three members of the family of low clouds (below 2000 meters [6500 feet]): *stratus*, *stratocumulus*, and *nimbostratus*.

Stratus (St) clouds form in low, horizontal layers that on occasion may produce light drizzle or mist. White to light gray in color, stratus clouds have very uniform bases and appear to blanket the entire sky.

Stratus-like clouds that develop a scalloped bottom that appear as long parallel rolls or broken globular patches are called **stratocumulus** (Sc) (Figure 5.4). Although stratocumulus clouds are similar in appearance to altocumulus, they are located lower in the sky and consist of broken patches that are generally much larger than those of altostratus. A simple way to distinguish between these is to point your hand in the direction of an individual cloud mass, and if the cloud is about the size of your thumbnail, it is an altocumulus; if it is the size of your fist, it is a stratocumulus cloud.

Figure 5.4 **Stratocumulus clouds commonly form over midlatitude oceans**

Satellite view of a large bank of stratocumulus clouds over the Pacific Ocean just south of San Diego, California.



Stratocumulus clouds often cover vast stretches of the subtropical oceans, which provide a ready supply of surface moisture. Because stratocumulus clouds cover such large areas, they are extremely important for Earth's energy balance, primarily because they reflect considerable amounts of incoming solar radiation.

Nimbostratus (Ns) clouds derive their name from the Latin *nimbus*, "rain cloud," and *stratus*, "to cover with a layer" (Figure 5.5). Nimbostratus clouds tend to produce constant precipitation and low visibility. These clouds normally form under stable conditions when air is forced to rise, as along a front (discussed in Chapter 9). Such forced ascent of stable air leads to the formation of a stratified cloud deck that is widespread and that may grow into the middle level of the troposphere. Precipitation associated with nimbostratus clouds is generally light to moderate (but can be heavy), is usually of long duration, and covers a large area.

Figure 5.5 Nimbostratus clouds are significant precipitation producers

These dark gray layers often exhibit a ragged-appearing base.

Clouds of Vertical Development

Clouds having their bases in the low height range and extending upward into the middle or high altitudes are called **clouds of vertical development** (see Figure 5.1). The most familiar type, **cumulus** (Cu) clouds, are individual masses that develop into vertical domes or towers having tops that resemble a head of cauliflower. Cumulus clouds most often form on clear days when unequal surface heating causes parcels of air to rise convectively above the lifting condensation level (Figure 5.6).

Figure 5.6 Cumulus clouds, often called "fair-weather clouds"

These small, white, billowy clouds generally form on sunny days.

When cumulus clouds are present early in the day, we can expect an increase in cloudiness in the afternoon as solar heating intensifies. Furthermore, because small cumulus clouds (*cumulus humilis*) form on “sunny” days and rarely produce appreciable precipitation, they are often called “fair-weather clouds.” However, when the air is unstable, cumulus clouds can grow dramatically in height. As such a cloud grows, its top enters the middle height range, and it is called a *cumulus congestus*. Finally, if the cloud continues to grow and rain begins to fall, it is called a *cumulonimbus*.

Cumulonimbus (Cb) are large, dense, billowy clouds of considerable vertical extent in the form of huge towers (Figure 5.7). In late stages of development, the upper part of a cumulonimbus turns to ice, appears fibrous, and frequently spreads out in the shape of an anvil as rising air spreads out at the tropopause. Cumulonimbus towers extend from a few hundred meters above the surface upward to 12 kilometers (7 miles) or, in the tropics, 20 kilometers (12 miles). These huge towers, commonly known as thunderstorm clouds, are capable of producing heavy precipitation with accompanying lightning, hail, and occasionally tornadoes. We consider the development of these important weather producers in Chapter 10.

Figure 5.7 Cumulonimbus clouds

These dense, billowy clouds have great vertical extent and can produce heavy precipitation and violent thunderstorms.

Eye on the Atmosphere 5.1

The cap cloud perched above this mountain may remain in place for hours. Cap clouds belong to a group referred to as *orographic clouds*.

Apply What You Know

1. Describe how these clouds form, based on the term *orographic clouds*.
2. Why does this cloud have a relatively flat bottom?
3. Cap clouds are related to another cloud type having a very similar shape. Can you name the cloud type?

Cloud Varieties

The 10 basic cloud types can be further subdivided into varieties that are named using adjectives that describe particular cloud characteristics. For example, the term *uncinus*, meaning "hook shaped," is applied to streaks of cirrus clouds that are shaped like a comma resting on its side. These *cirrus uncinus* are often precursors of bad weather.

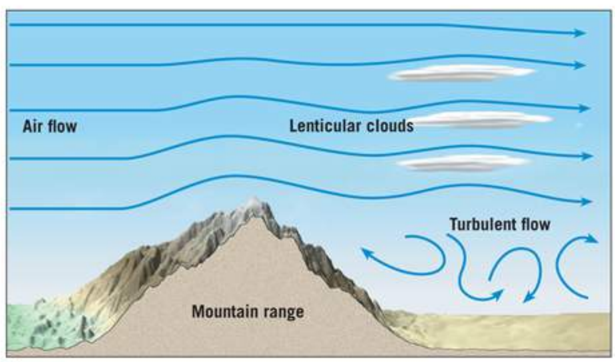
When stratus or cumulus clouds appear broken (or fractured), the adjective *fractus* is used in their description. In addition, some clouds have rounded protuberances on their bottom surface, similar to a cow udder. When these structures are present, the term *mammatus* is applied. This configuration is usually associated with stormy weather and cumulonimbus clouds.

Stationary lens-shaped clouds, called **lenticular clouds** (formal name *altocumulus lenticularis*), are common in rugged or mountainous topographies (Figure 5.8A). Although lenticular clouds can develop whenever the airflow develops a wavy pattern, they most frequently form on the leeward side of mountains. As moist stable air passes over mountainous terrain, a series of standing waves form on the downwind side, as shown in Figure 5.8B. As the air ascends the wave crest, it cools adiabatically. If the air reaches its dew point temperature, moisture in the air will condense to form a lenticular cloud. As the moist air moves down into the trough of the wave, the cloud droplets evaporate, leaving areas with descending air cloud-free.

Figure 5.8 **Lenticular clouds**

A. These lens-shaped clouds are relatively common in mountainous areas. **B.** This diagram depicts the formation of lenticular clouds in the turbulent flow that develops in the lee of a mountain range.

A.



B.

Watch **Video: Is That a Cloud?**

Concept Checks 5.2

- What are the two criteria by which clouds are classified?
- Why are high clouds always thin in comparison to low and middle clouds?
- List the 10 basic cloud types, and describe each based on its form (shape) and height (altitude).

5.3 Types of Fog

LO 3 Identify the basic types of fog and describe how each forms.

Fog is defined as *a cloud with its base at or very near the ground*. Physically, there are no differences between fog and a cloud; their appearances and structures are the same. The essential difference is the method and place of formation. Whereas clouds result when air rises and cools adiabatically, fog results from cooling or when air becomes saturated through the addition of water vapor (evaporation fog) rather than the changes in pressure that cool rising air.

Although not inherently dangerous, fog is generally considered an atmospheric hazard (Figure 5.9). During daylight hours, fog reduces visibility to 2 or 3 kilometers (1 or 2 miles). When the fog is particularly dense, visibility may be cut to a few dozen meters or less, making travel by any mode difficult and dangerous. Official weather stations report fog only when it is thick enough to reduce visibility to 1 kilometer (0.6 mile) or less. Table 5.2 summarizes the basic fog types.

Figure 5.9 Radiation fog is generated by radiation cooling of Earth's surface

A. Satellite image of dense fog in California's San Joaquin Valley on November 20, 2002. This early-morning radiation fog was responsible for several car accidents in the region, including a 14-car pileup. The white areas to the east of the fog are the snow-capped Sierra Nevadas.
B. Radiation fog can make a morning commute quite hazardous.

Watch Video: Clouds and Aviation

Table 5.2 **Basic Fog Types**

Fog Groups	Fog Types	Mode of Formation and Characteristics
Fogs formed by cooling	Radiation fog	A nighttime phenomenon generated by radiation cooling of the ground and adjacent air. Usually forms in valleys, with the surrounding hills fog free.
	Advection fog	Forms when warm, moist air flows over a cold surface and is chilled from below. Often a wintertime phenomenon in the Midwest, forming when warm air from the Gulf of Mexico flows inland or when moist air flows over a cool ocean current.
	Upslope fog	When air flows up a mountain slope, or sometimes a gradually sloping landform, it expands and cools adiabatically.
Fogs formed by the addition of water vapor	Steam fog	When cool air moves over warm water, enough moisture may evaporate from the water surface to saturate the air above. Common on autumn mornings when the air is cool and the water in lakes or streams is still relatively warm.
	Frontal (precipitation) fog	Forms when raindrops falling from warm air above a frontal surface evaporate into the cooler air below and cause saturation. A wintertime phenomenon that produces cool damp days.

Fogs Formed by Cooling

When the temperature of a layer of air in contact with the ground falls below its dew point, condensation produces fog. Depending on the prevailing conditions, fogs formed by cooling are called either *radiation fog*, *advection fog*, or *upslope fog*.

> Fog formed by cooling air to its dew-point temperature includes radiation fog, advection fog, and upslope fog.

Radiation Fog

As the name implies, **radiation fog** results from radiation cooling of the ground and adjacent air. It is a nighttime phenomenon that requires clear skies, high relative humidity, and relatively light wind. Under clear skies, the ground and the air immediately above cool rapidly. Because of the high relative humidity, a small amount of cooling lowers the temperature to the dew point. If the air is calm, the fog is usually patchy and less than 1 meter (3 feet) deep. For radiation fog to be more extensive vertically, a light breeze of 3 to 5 kilometers (2 to 3 miles) per hour is necessary, to create enough turbulence to carry the fog upward 10 to 30 meters (30 to 100 feet) without dispersing it. High winds, in contrast, mix the air with drier air above and disperse the fog.

Because the air containing the fog is relatively cold and dense, it flows downslope in hilly terrain. As a result, radiation fog is thickest in valleys, whereas the surrounding hills may remain clear (Figure 5.9A). Normally, radiation fog dissipates within 1 to 3 hours after sunrise—and is often said to “lift.” However, the fog does not actually “lift.” Instead, as the Sun warms the ground, the lowest layer of air is heated first, and the fog evaporates from the bottom up. The last vestiges of radiation fog may appear as a low layer of stratus clouds.

Advection Fog

When warm, moist air blows over a cold surface, it becomes chilled by contact with the cold surface below. If cooling is sufficient, the result will be a blanket of fog called **advection fog**. (The term *advection* refers to air moving horizontally.) A classic example is the frequent advection fog around San Francisco's Golden Gate Bridge (Figure 5.10). The fog experienced in San Francisco, California, as well as many other west coast locations, is produced when warm, moist air from the Pacific Ocean moves over the cold California Current.

Figure 5.10 Advection fog forms when warm, moist air moves over a cool surface

This fog bank, rolling into San Francisco Bay, was generated as moist air passed over the cold California Current.

A certain amount of turbulence is needed for proper development of advection fog; typically winds between 10 and 30 kilometers (6 and 18 miles) per hour are required. Not only does the turbulence facilitate cooling through a thicker layer of air, but it also carries the fog to greater heights. Thus, advection fogs often extend 300 to 600 meters (1000 to

2000 feet) above the surface and persist longer than radiation fogs. An example of such fog can be found at Cape Disappointment, Washington—the foggiest location in the United States. The name is indeed appropriate because the station averages about 2552 hours of fog each year—equivalent to 106 days.

Advection fog is also a common wintertime phenomenon in the Southeast and Midwest when relatively warm, moist air from the Gulf of Mexico and Atlantic moves over cold and occasionally snow-covered surfaces to produce widespread foggy conditions. This type of advection fog tends to be thick and can produce hazardous driving conditions.

Upslope Fog

As its name implies, **upslope fog** forms when relatively humid air moves up a gradually sloping landform or, in some cases, up the steep slopes of a mountain (Figure 5.11). Because of the upward movement, air expands and cools adiabatically. If the dew point is reached, an extensive layer of fog will form.

Figure 5.11 **Upslope fog forms when relatively humid air moves up sloping terrain**

It is easy to visualize how upslope fog might form in mountainous terrain. However, in the United States, upslope fog also occurs in the Great Plains, when humid air moves from the Gulf of Mexico toward the Rocky Mountains. (Recall that Denver, Colorado, is called the "mile-high city" and that the Gulf of Mexico is at sea level.) Air flowing "up" the Great Plains expands and cools adiabatically by as much as 12°C (22°F), which can result in extensive upslope fog in the western plains.

Evaporation Fogs

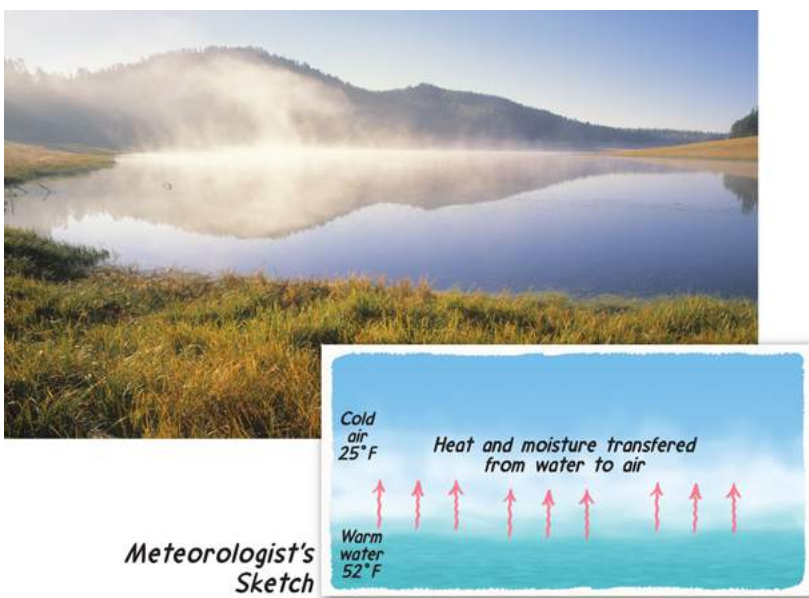
When saturation occurs primarily because of the addition of water vapor to air, the resulting fogs are called *evaporation fogs*. Two types of evaporation fogs are recognized: *steam fog* and *frontal (precipitation) fog*.

Steam Fog

When cool, unsaturated air moves over a warm water body, enough moisture may evaporate to saturate the air directly above, generating a layer of fog. The added moisture and energy often makes the saturated air buoyant enough to cause it to rise. Because the foggy air looks like the "steam" that forms above a hot cup of coffee, the phenomenon is called **steam fog** (Figure 5.12). Steam fog is a fairly common occurrence over lakes and rivers on clear, crisp mornings in the autumn when the water is still relatively warm but the air is comparatively cold. Steam fog usually forms a shallow foggy layer because as it rises, the fog droplets mix with the cool unsaturated air above and dissipate (evaporate).

Figure 5.12 **Steam fog occurs in the fall when cool air flows over a comparatively warm water body**

This image shows steam fog rising from Sierra Blanca Lake, Arizona.



> Evaporation fogs, the result of evaporation of water that is warmer than the surrounding air, include steam fog and precipitation fog.

In a few settings, steam fogs can be dense—especially during the winter, as cold arctic air pours off the continents and ice shelves over the comparatively warm open ocean. The temperature contrast between the warm ocean surface and overlying cold air mass has been known to exceed 30°C (54°F). The result is thick steam fog produced as the rising water vapor saturates a large volume of air. Because of its source and appearance, this type of dense steam fog is given the name *arctic sea smoke*.

You might have wondered . . .

Why do I see my breath on cold mornings?

On cold days when you "see your breath," you are actually creating steam fog. The moist air that you exhale saturates a small volume of cold air, causing tiny droplets to form. As with steam fogs, the droplets quickly evaporate as the "fog" mixes with the unsaturated air around it.

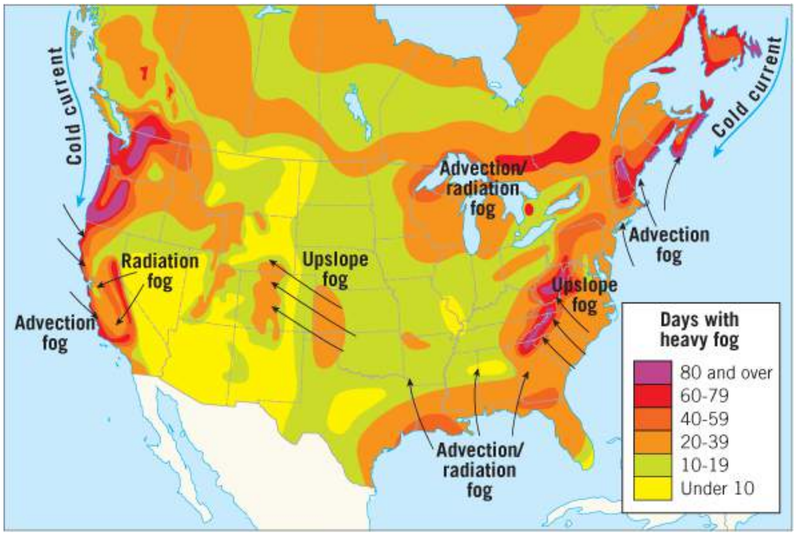
Frontal (Precipitation) Fog

Frontal boundaries where a warm, moist air mass is forced to rise over cooler, dryer air below generates **frontal (precipitation) fog**. The foggy conditions result because the raindrops falling from relatively warm air above the frontal surface evaporate in the cooler air below, causing the cooler air to become saturated. Frontal fog, which can be quite thick, is most common on cool days during extended periods of light rainfall. Although less common, it is possible for frontal fog to form behind a cold front by the same process.

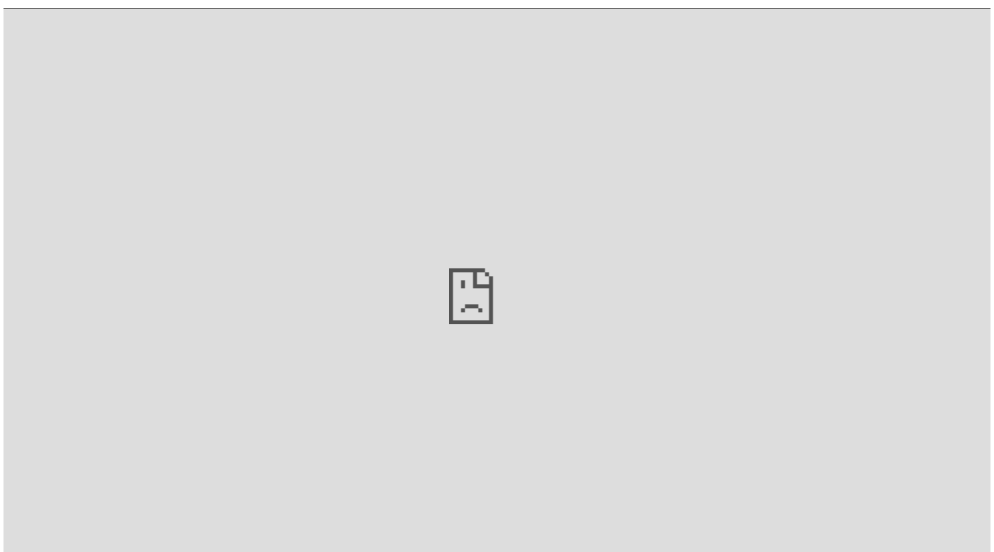
Figure 5.13 shows the predominant fog type and frequency of dense fog for various locations. As might be expected, fog incidence is highest in coastal areas, especially where cold currents prevail, as along the Pacific and New England coasts. Relatively high frequencies are also found in the Great Lakes region and in the humid Appalachian Mountains of the Eastern United States. In contrast, fogs are rare in the interior of the continent, especially in the arid and semiarid areas of the West (the yellow areas in Figure 5.13).

Smartfigure 5.13 **Map showing average numbers of days per year with heavy fog**

Coastal areas where cold currents prevail, particularly the Pacific Northwest and New England, have high occurrences of dense fog.



Watch **SmartFigure: Fog**



Concept Checks 5.3

- Distinguish between clouds and fog.
- List five types of fog and discuss how they form.
- What actually happens when a radiation fog "lifts"?

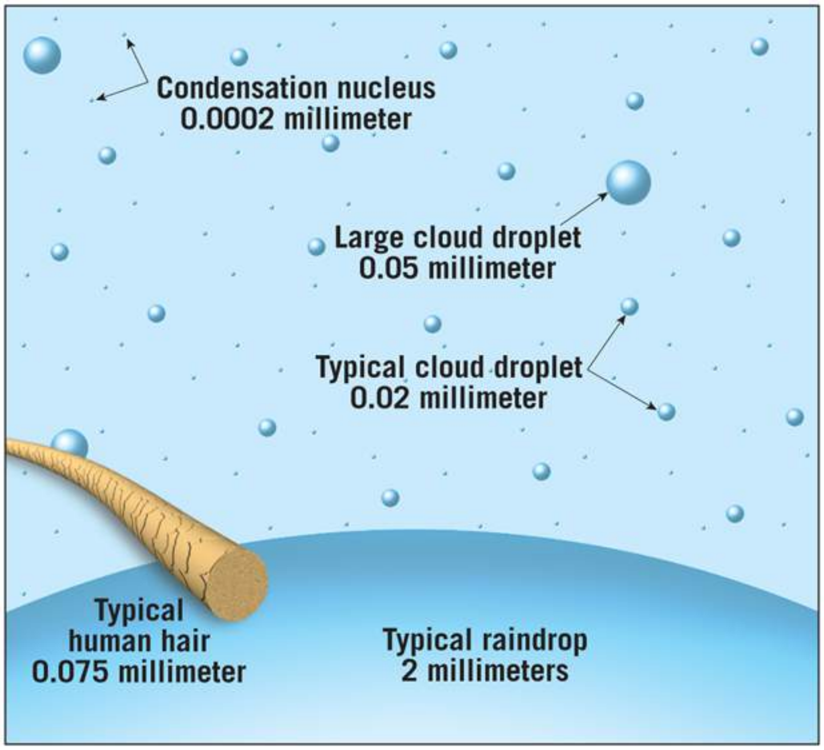
5.4 How Precipitation Forms

LO 4 Describe the Bergeron process and explain how it differs from the collision–coalescence process.

If all clouds contain water, why do some produce precipitation while others drift placidly overhead? This seemingly simple question perplexed meteorologists for many years.

Typical cloud droplets are minuscule—20 micrometers (0.02 millimeter) in diameter (Figure 5.14). In comparison, a human hair is about 75 micrometers in diameter. Because of their small size, cloud droplets fall through still air incredibly slowly. An average cloud droplet falling from a cloud base at 1000 meters (3280 feet) would require several hours to reach the ground. However, it would never complete its journey. Instead, the cloud droplet would evaporate before it fell a few meters from the cloud base into the unsaturated air below.

Figure 5.14 Diameters of particles involved in condensation and precipitation processes



How large must a cloud droplet grow in order to fall as precipitation? A typical raindrop has a diameter of about 2 millimeters, or 100 times that of the average cloud droplet (Figure 5.14). However, the *volume* of a typical raindrop is 1 million times that of a cloud droplet. Thus, for precipitation to form, cloud droplets must grow in volume by roughly 1 million times. You might suspect that additional condensation creates drops large enough to survive the descent to the surface. However, clouds consist of many billions of tiny cloud droplets that all compete for the available water. Thus, condensation provides an inefficient means of raindrop formation.

> A typical raindrop has a *volume* 1 million times that of a cloud droplet.

Two processes are responsible for the formation of precipitation: the *Bergeron process* and the *collision–coalescence process*.

Precipitation from Cold Clouds: The Bergeron Process

The **Bergeron process**, which generates much of the precipitation in the middle and high latitudes, is named for its discoverer, the highly respected Swedish meteorologist Tor Bergeron. To understand how this mechanism operates, we must first examine two important properties of water.

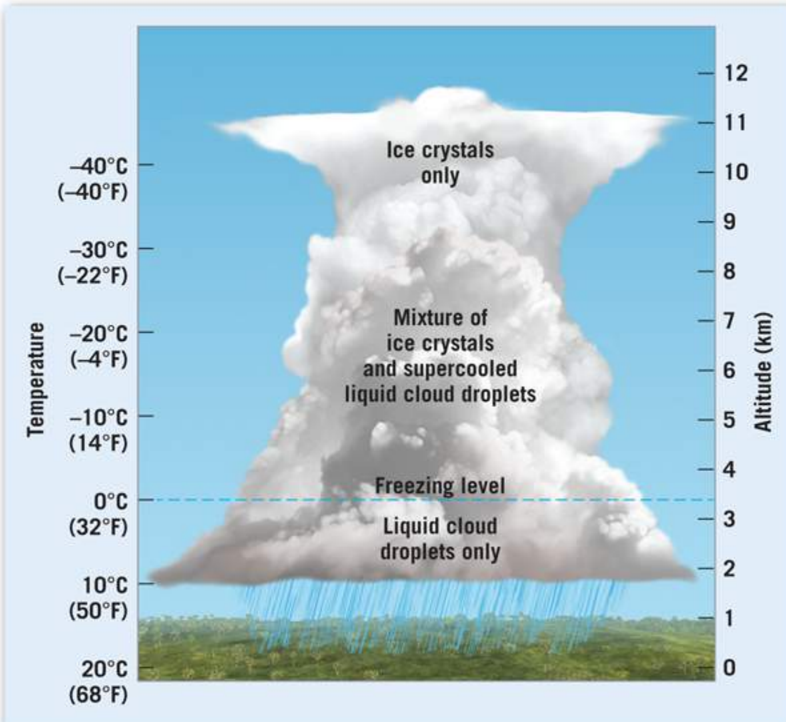
Supercooled Water

The Bergeron process operates in *cold clouds* at temperatures below 0°C (32°F), where liquid cloud droplets and ice crystals coexist. Contrary to what you might expect, *cloud droplets do not usually freeze at 0°C (32°F)*. In order for water to freeze, it must first cool to its freezing temperature, which causes the water molecules to slow down. Next, the molecules need to bond together to form ice crystals, which requires the loss of even more energy. In fact, pure water will not freeze until it reaches a temperature of about −40°C (−40°F). Water in the liquid state below 0°C (32°F) is referred to as **supercooled water**. However, supercooled water readily freezes if it collides with an object, which explains why airplanes collect ice when they pass through a cold cloud of supercooled droplets. Supercooled water droplets also cause *freezing rain*, which falls as a liquid but then turns to a sheet of ice when it strikes the pavement, tree branches, and car windshields.

In the atmosphere, supercooled droplets freeze on contact with solid particles that have a shape closely resembling that of ice (silver iodide, for example). These materials, called **freezing nuclei**, are sparse in the atmosphere and do not generally become effective until the air temperature is about −15°C (5°F) or colder. Thus, at temperatures between 0 and −15°C, most clouds consist only of supercooled water droplets (Figure 5.15). Between −15 and −40°C, most clouds consist of supercooled droplets that coexist with ice crystals, and at temperatures colder than −40°C (−40°F), clouds are composed entirely of ice crystals. For example, the tops of towering cumulonimbus clouds and wispy high-altitude cirrus clouds are usually composed entirely of ice crystals.

Figure 5.15 **Distribution of cloud particles found in towering cumulonimbus clouds**

Temperature at different heights within these clouds determine where liquid droplets or ice crystals are found.



Saturation Vapor Pressure over Water Versus over Ice

Another important property of water is that *the saturation vapor pressure above ice crystals is lower than above water droplets*. Stated another way, when the air surrounding a water droplet is saturated (100 percent relative humidity), it is supersaturated relative to a nearby ice crystal. For example, Table 5.3 shows that at –10°C (14°F), when the relative humidity is 100 percent with respect to *water*, the relative humidity with respect to *ice* is about 110 percent. This is because ice crystals are solid, so the individual ice molecules are held together more tightly than those of a liquid droplet. For the same reason, water vapor molecules escape (evaporate) from water droplets at a faster rate than from ice crystals at the same temperature.

Table 5.3 Relative Humidity with Respect to Ice When Relative Humidity with Respect to Water Is 100 Percent

Temperature (°C)	Relative Humidity with Respect to:	
	Water	Ice
0	100%	100%
–5	100%	105%
–10	100%	110%
–15	100%	115%
–20	100%	121%

Eye on the Atmosphere 5.2

This satellite image shows a layer of low-lying clouds moving eastward into the bays and waterways of the northwestern United States. Lining the coast are the forested Coast Ranges, and further inland is the Cascade Range, which includes several large volcanoes.

Apply What You Know

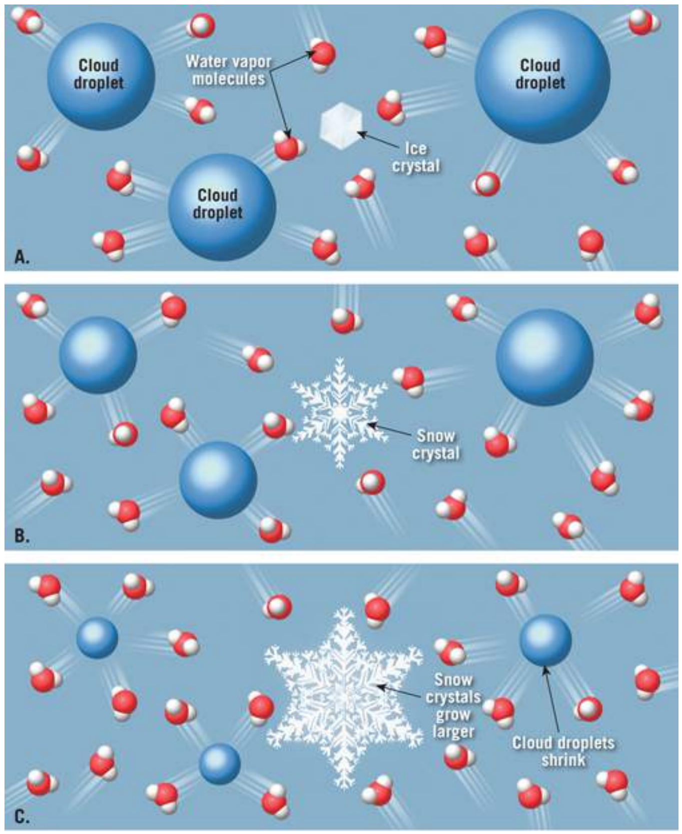
1. Why do you think the clouds formed over the ocean while the land areas are cloud free?
2. Why are the mountainous areas of western Washington State covered with lush vegetation while much of the eastern half of the state appears semiarid?

How the Bergeron Process Generates Precipitation

When ice crystals and supercooled water droplets coexist, the conditions are ideal for creating precipitation. Because freezing nuclei are sparse, cold clouds consist of relatively few ice crystals (snow crystals) surrounded by numerous liquid droplets (Figure 5.16A). Since the air is supersaturated with respect to the comparatively few ice crystals, the water molecules will begin to collect on the ice crystals by the process of deposition. This in turn lowers the overall relative humidity of the air as the water vapor becomes solid. In response, the surrounding water droplets will begin to evaporate to replenish the lost water vapor (Figure 5.16B). Thus the growth of ice crystals is fed by the continued evaporation and shrinkage of the liquid droplets (Figure 5.16C).

Figure 5.16 The Bergeron process

Ice crystals grow at the expense of cloud droplets until they are large enough to fall. **A.** As water vapor is deposited on ice crystals, liquid water evaporates from the cloud droplets to maintain air saturation. The ice crystals grow, while the cloud droplets become smaller (**B**, **C**).



When ice crystals become sufficiently large, they begin to fall because of gravity. Air movement will sometimes break up these delicate crystals, and the fragments will serve as new freezing nuclei that draw water vapor from other liquid droplets. A chain reaction ensues and produces many ice crystals, which grow into *snowflakes*.

The Bergeron process can produce precipitation throughout the year in the middle latitudes, provided that at least a portion of a cloud is cold enough, about −15°C (5°F), to generate ice crystals. The type of precipitation (snow, sleet, rain, or freezing rain) that reaches the ground depends on the temperature profile in the lower few kilometers of the atmosphere. When the surface temperature is above 4°C (39°F), snowflakes usually melt before they reach the ground and continue their descent as rain. Even on a hot summer day, a heavy rainfall may have begun as a snowstorm high in the clouds overhead. During a middle-latitude winter, even low clouds are cold enough to trigger precipitation via the Bergeron process.

> The Bergeron process occurs in cold clouds, where water vapor is deposited on ice crystals, lowering the relative humidity of the air. This causes the surrounding water droplets to evaporate and replenish the lost water vapor.

Precipitation from Warm Clouds: The Collision–Coalescence Process

The **collision–coalescence process** is the dominant process for generating precipitation in *warm clouds*—clouds with tops warmer than −15°C (5°F). Simply, the collision–coalescence process involves multiple collisions of tiny cloud droplets that stick together (coalesce) to form raindrops large enough to reach the ground before evaporating.

One of the requirements for the formation of raindrops by the collision–coalescence process is the presence of larger-than-average cloud droplets. Research has shown that clouds made entirely of liquid droplets usually contain some droplets larger than 20 micrometers (0.02 millimeter). These relatively large droplets may form when "giant" condensation nuclei are present or when hygroscopic particles (such as sea salt) are carried by updrafts into the atmosphere. Hygroscopic particles begin to collect water vapor at relative humidity below 100 percent. When large cloud droplets are intermixed with numerous smaller droplets, the conditions are ideal for the formation of precipitation.

Cloud Droplet Size and Fall Velocities

The maximum speed at which an object falls, called its *terminal velocity*, occurs when air resistance equals the gravitational pull on the object. Because large droplets have a smaller ratio of surface area as compared to their weight, they fall faster than small droplets. Imagine that you go skydiving while wearing a baseball cap. As you make the jump, your cap comes off. Because your body has a low ratio of surface area compared to your weight, you will have a much higher terminal velocity than your baseball cap. Table 5.4 summarizes how this principle applies to cloud droplets and their fall velocities.

Table 5.4 Fall Velocity of Water Drops

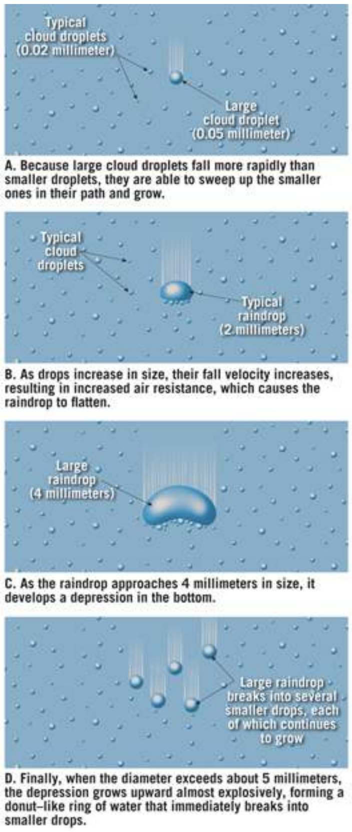
Types	Diameter (millimeters)	Fall Velocity (km/hr)	Fall Velocity (mi/hr)
Small cloud droplets	0.01	0.01	0.006
Typical cloud droplets	0.02	0.04	0.03
Large cloud droplets	0.05	0.3	0.2
Drizzle droplets	0.5	7	4
Typical rain drops	2.0	23	14
Large rain drops	5.0	33	20

Data from Smithsonian Meteorological Tables.

As the larger droplets fall through a cloud, they collide with smaller, slower droplets and coalesce. They become larger in the process and fall even more rapidly (or, in an updraft, they rise more slowly), which increases their chances of more collisions and growth (Figure 5.17A). After a million or so cloud droplets coalesce, they form a raindrop that is large enough to fall to the surface without evaporating.

Figure 5.17 The collision–coalescence process

The collision–coalescence process involves multiple collisions of tiny cloud droplets that stick together (coalesce) to form raindrops large enough to reach the ground before evaporating.



Because of the huge number of collisions required for growth to raindrop size, clouds that have great vertical thickness and contain large cloud droplets have the best chance of producing precipitation. Updrafts associated with unstable air also aid this process because the droplets can traverse the cloud repeatedly, which results in more collisions.

As raindrops grow in size, their fall velocity increases. This in turn increases the frictional resistance of the air, which causes the drop's "bottom" to flatten out (Figure 5.17B). As a drop approaches 4 millimeters in diameter, it develops a depression, as shown in Figure 5.17C. Raindrops can grow to a maximum of 5 millimeters when they fall at the rate of 33 kilometers (20 miles) per hour. At this size, the water's surface tension, which holds the drop together, is surpassed by the frictional drag of the air. The depression grows almost explosively, forming a donutlike ring that immediately breaks apart. The resulting breakup of a large raindrop produces numerous smaller drops that begin anew the task of sweeping up cloud droplets (Figure 5.17D).

> The collision–coalescence process occurs in warm clouds, where large cloud drops grow by collecting smaller droplets.

How Do Cloud Droplets Coalesce?

The collision–coalescence process is not as simple as it may first seem. First, as the larger droplets descend, they produce an airstream around them similar to that produced by an automobile traveling rapidly down the highway. The airstream sweeps aside objects, especially the smallest cloud droplets. Imagine driving on a summer night along a country road. The bugs in the air are like cloud droplets: Most are pushed aside, but larger bugs (cloud droplets) have an increased chance of colliding with the car (giant droplet).

Further, collision does not guarantee coalescence. Experimentation has indicated that the presence of atmospheric electricity may be the key to what holds these droplets together once they collide. If a droplet with a negative charge collides with a positively charged droplet, their electrical attraction may bind them together.

The air over the tropical oceans is an ideal setting for the development of precipitation by the collision–coalescence process because the relatively clean air contains fewer condensation nuclei compared to the air over populated urban regions. With fewer condensation nuclei to compete for available water vapor (which is plentiful), condensation is fast-paced and produces comparatively few large cloud droplets. Within developing cumulus clouds, the largest drops quickly gather smaller droplets to generate the warm afternoon showers associated with tropical climates.

In the middle latitudes, the collision–coalescence process contributes to the precipitation from a large cumulonimbus cloud by working in tandem with the Bergeron process—particularly during the hot, humid summer months. High in these towers, the Bergeron process generates snow that melts as it passes below the freezing level. When snowflakes melt, they generate relatively large drops with fast fall velocities. As these large drops descend, they overtake and coalesce with the slower and smaller cloud droplets that comprise much of the lower regions of the cloud. The result can be a heavy downpour.

Concept Checks 5.4

- Describe the Bergeron process.
- Explain how snow that formed high in a towering cloud might produce rain.
- Briefly summarize the collision–coalescence process.

5.5 Forms of Precipitation

LO 5 Describe the atmospheric conditions that produce rain, snow, sleet, freezing rain, and hail.

Atmospheric conditions vary greatly both geographically and seasonally, resulting in several different types of precipitation (Figure 5.18). Rain and snow are the most common and familiar forms, but others, listed in Table 5.5, are important as well. Sleet, freezing rain (glaze), and hail often produce hazardous weather and occasionally inflict considerable damage.

Figure 5.18 Four precipitation types and their temperature profiles

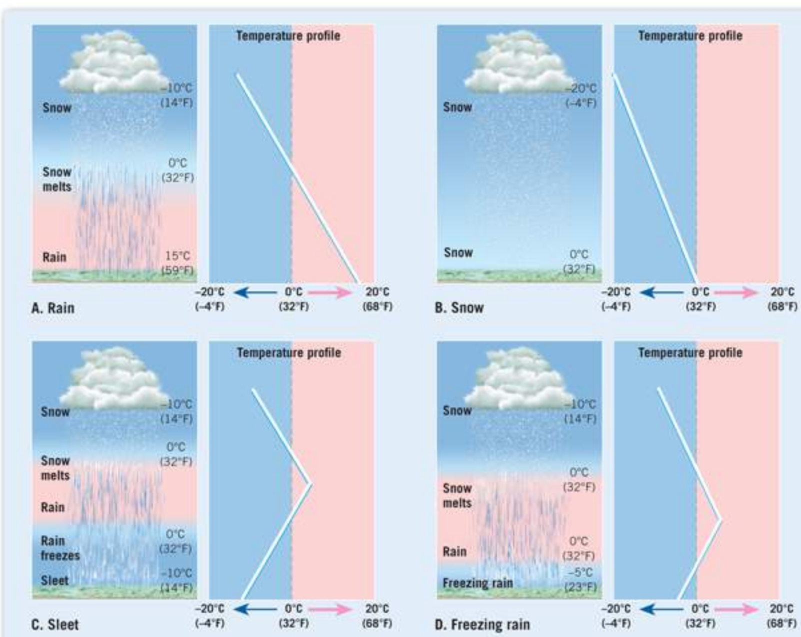


Table 5.5 **Types of Precipitation**

Type	Approximate Size	State of Water	Description
Mist	0.005–0.05 mm	Liquid	Droplets large enough to be felt on the face when air is moving 1 meter/second. Associated with stratus clouds.
Drizzle	0.05–0.5 mm	Liquid	Small, uniform droplets that fall from stratus clouds, generally for several hours.
Rain	0.5–5 mm	Liquid	Generally produced by nimbostratus or cumulonimbus clouds. When heavy, size can be highly variable from one place to another.
Sleet	0.5–5 mm	Solid	Small, spherical to lumpy ice particles that form when raindrops freeze while falling through a layer of subfreezing air beneath nimbostratus clouds. Because the ice particles are small, any damage is generally minor. Sleet can make travel hazardous.
Freezing Rain (glaze)	Layers 1 mm–2 cm thick	Solid	Produced when supercooled raindrops freeze on contact with solid objects beneath nimbostratus clouds. Freezing rain can form a thick coating of ice that has sufficient weight to seriously damage trees and power lines.
Rime	Variable accumulations	Solid	Deposits usually consisting of ice feathers that point into the wind. These delicate frostlike accumulations form as supercooled cloud or fog droplets encounter objects and freeze on contact.
Snow	1 mm–2 cm	Solid	The crystalline nature of snow allows it to assume many shapes, including six-sided crystals, plates, and needles. Produced when water vapor is deposited as ice crystals that remain frozen during their descent from nimbostratus clouds.
Graupel	2–5 mm	Solid	"Soft hail" that forms as rime collects on snow crystals to produce irregular masses of "soft" ice. Because these particles are softer than hailstones, they normally flatten out upon impact.
Hail	5–10 cm or larger	Solid	Precipitation in the form of hard, rounded pellets or irregular lumps of ice. Produced in large convective cumulonimbus clouds, where ice particles and supercooled water coexist.

Rain

In meteorology, the term **rain** is restricted to drops of water that fall from a cloud and have a diameter of at least 0.5 millimeter. Most rain originates in either nimbostratus clouds or in towering cumulonimbus clouds that are capable of producing unusually heavy rainfalls known as *cloudbursts*.

As rain enters the unsaturated air below the cloud, it begins to evaporate. Depending on the humidity of the air and the size of the drops, rain may completely evaporate before reaching the ground. This phenomenon produces **virga**, which appear as streaks of precipitation falling from a cloud that extend toward Earth's surface without reaching it. Similar to virga, ice crystals may sublimate when they enter the dry air below. These wisps of ice particles are called **fallstreaks**.

Fine, uniform droplets of water with diameters less than 0.5 millimeters are called **drizzle**. Drizzle and small raindrops generally are produced in stratus or nimbostratus clouds, from which precipitation may be continuous for several hours or, on rare occasions, for days.

Precipitation containing the very smallest droplets able to reach the ground is called **mist**. Mist can be so fine that the tiny droplets appear to float, and their impact is almost imperceptible. Mist closely resembles fog. Meteorologists use the word *fog* when the visibility is less than 1 kilometer (0.6 miles) and *mist* when the visibility is greater than 1 kilometer.

> Rain reaches Earth's surface when the temperature near the ground is above freezing.

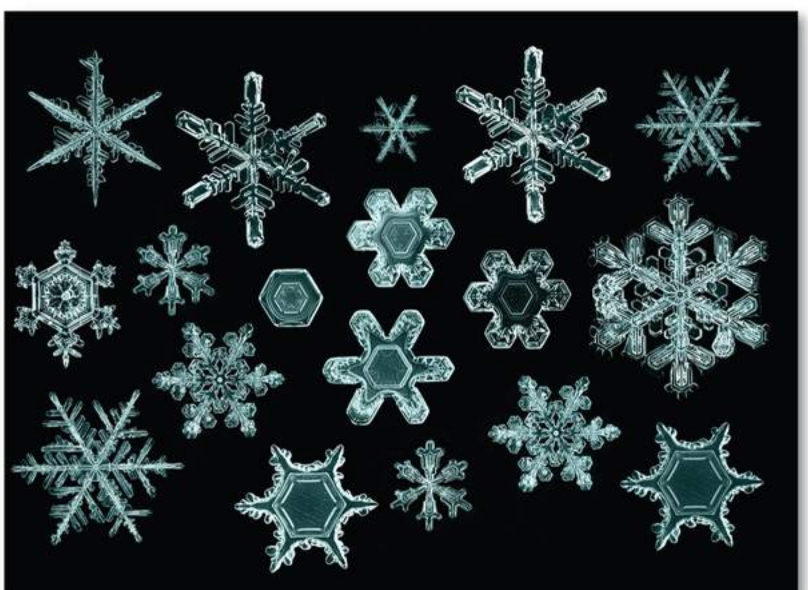
Snow

Snow is winter precipitation in the form of ice crystals, or aggregates of ice crystals. The size, shape, and concentration of snowflakes depend to a great extent on the temperature profile of the atmosphere.

Recall that at very low temperatures, the moisture content of air is low. The result is the generation of very light and fluffy snow made up of individual six-sided ice crystals (Figure 5.19). This is the "powder" that downhill skiers covet. By contrast, at temperatures warmer than about −5°C (23°F), the ice crystals may join together into larger clumps consisting of tangled aggregates of crystals. Snowfalls consisting of these composite snowflakes are generally heavy and have a high moisture content, which makes them ideal for making snowballs.

Figure 5.19 Snow crystals

Snow crystals are usually six-sided, but they come in an infinite variety of forms. The snowflakes that reach the ground often consist of multiple ice crystals stuck together.



Snow can reach Earth's surface when the temperature of a thin layer of air near the ground is above freezing. In this situation, the snow does not have enough time to melt before reaching the ground. This type of snow is usually quite wet.

> Snow reaches Earth's surface when the temperature at the ground is near or below freezing.

Under certain atmospheric conditions, falling snow crystals grow as they intercept tiny supercooled cloud droplets that freeze on them. The resulting snowflakes are described as being *rimed*. If riming continues and makes the shape of the original six-sided snow crystal no longer identifiable, the soft ice pellet is called **graupel**. Usually oblong in shape and fragile enough that it will fall apart when touched, graupel is also known as *soft hail* or *snow pellets*.

You might have wondered . . .

What is the snowiest city in the United States?

According to National Weather Service records, Rochester, New York, is the snowiest U.S. city, averaging nearly 239 centimeters (94 inches) of snow annually. However, Buffalo, New York, is a close runner-up.

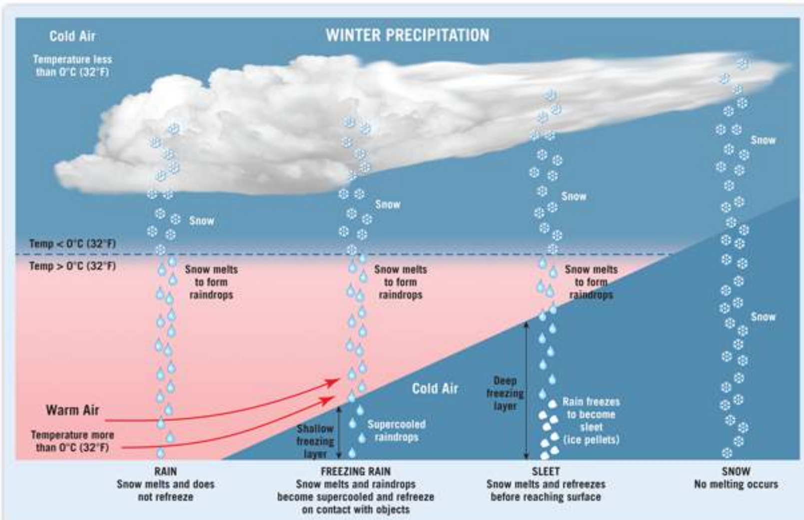
Sleet and Freezing Rain

Sleet, a wintertime phenomenon, consists of clear to translucent ice pellets. Depending on intensity and duration, sleet can cover the ground much like a thin blanket of snow. **Freezing rain**, also called **glaze**, in contrast, falls as supercooled raindrops that freeze on contact with roads, power lines, and other structures.

As shown in Figure 5.20, both sleet and freezing rain occur mainly in the winter and early spring. They most often form along a warm front where a mass of relatively warm air is forced over a layer of subfreezing air near the ground. Both begin as snow, which melts to form rain as it falls through the layer of warm air below the frontal boundary. When the newly formed raindrops encounter a shallow warm layer that overlies a thick cold layer of air, *sleet* results (Figure 5.20). In this setting, the snowflakes mostly melt, except for tiny ice crystals that remain in the drop. As these raindrops fall through the thick layer of subfreezing air, they refreeze and reach the ground as small pellets of ice roughly the size of the raindrops from which they formed.

Figure 5.20 **Formation of sleet and freezing rain**

When rain passes through a cold layer of air and freezes, the resulting ice pellets are called *sleet*. Freezing rain forms under similar conditions, except the cold layer of air is not deep enough to refreeze the raindrops. These forms of precipitation occur often in the winter, when warm air (along a warm front) is forced over a layer of subfreezing air.



By comparison, if the warm layer is thick and the drop melts completely, then the shallow layer of cold air near the ground is not thick enough to cause the raindrops to refreeze. They instead become supercooled—that is, they remain liquid at temperatures below freezing. Upon striking subfreezing objects on Earth's surface, these supercooled raindrops instantly turn to ice—hence the term *freezing rain* (Figure 5.20). The result is thick coating of ice that has sufficient weight to break tree limbs, down power lines, and make walking and driving extremely hazardous.

> Freezing rain and sleet form when falling snow melts in a warm layer, then falls through a subfreezing layer. When the falling rain becomes supercooled and freezes on impact, it produces freezing rain; but if it freezes before reaching the ground, it forms sleet.

In January 1998 an ice storm of historic proportions caused enormous damage in New England and southeastern Canada. Five days of freezing rain deposited a heavy layer of ice on exposed surfaces from eastern Ontario to the Atlantic coast. The 8 centimeters (3 inches) of precipitation caused trees, power lines, and high-voltage towers to collapse, leaving over 1 million households without power—many for nearly a month following the storm (Figure 5.21). At least 40 deaths were blamed on the storm, which caused damages in excess of $3 billion. Much of the damage was to the electrical grid, which one Canadian climatologist summed up this way: "What it took human beings a half-century to construct, took nature a matter of hours to knock down."

Figure 5.21 Freezing rain results when supercooled raindrops freeze on contact with objects

In January 1998, an ice storm of historic proportions caused enormous damage in New England and southeastern Canada. Nearly 5 days of freezing rain (glaze) caused 40 deaths and more than $3 billion in damages, and it left millions of people without electricity—some for as long as a month.

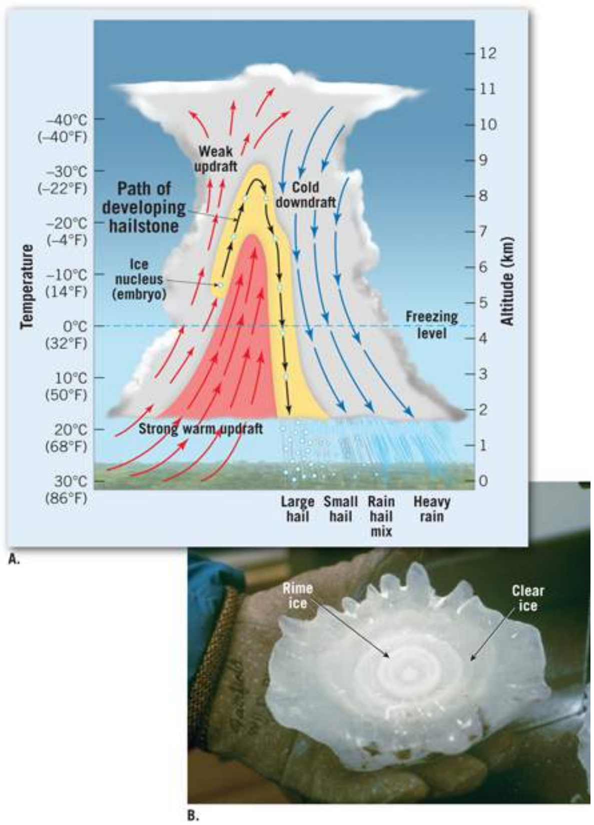
Hail

Hail is precipitation in the form of hard, rounded pellets or irregular lumps of ice with diameters of 5 millimeters (0.20 inches) or more. Hail is produced in the middle to upper reaches of tall cumulonimbus clouds, where updrafts can sometimes exceed speeds of 160 kilometers (100 miles) per hour and where the air temperature is below freezing. Hailstones begin as small embryonic ice pellets or graupel that coexist with supercooled droplets. The ice pellets grow by collecting supercooled water droplets, and sometimes other small pieces of hail, as they are lifted by updrafts within the cloud.

Cumulonimbus clouds that produce hail have a complex system of updrafts and downdrafts. As shown in Figure 5.22A, a region of intense updrafts suspends rain and hail aloft, producing a rain-free region surrounded by an area of downdrafts and heavy precipitation. The largest hailstones are generated around the core of the most intense zone of updraft, where they rise slowly enough to collect appreciable amounts of supercooled water. The process continues until the hailstone grows too heavy to be supported by the updraft or encounters a downdraft and falls to the surface.

Figure 5.22 **Formation of hailstones**

A. Hailstones begin as small ice pellets that grow through the addition of supercooled water droplets as they move through a cloud. Updrafts carry stones upward, increasing the size of the hail by adding layers of ice. Eventually, the hailstones grow too large to be supported by the updraft, or they encounter a downdraft. **B.** This cut hailstone, which fell over Coffeyville, Kansas, in 1970, originally weighed 0.75 kilogram (1.67 pounds).



> Hail consists of hard rounded pellets, or aggregates of pellets, that form high in towering cumulonimbus clouds.

It was once believed that hailstones traveled up and down many times through a cloud to form a large hailstone composed of spherical clear and milky layers. Recent research, however, indicates that there are two methods by which large hailstones develop, *wet growth* and *dry growth* (Figure 5.22B). Clear ice is produced by wet growth in regions of the cloud that contain abundant moisture, where colliding droplets coat the surface of the hailstones. The latent heat released keeps the outside of the stone wet. As these droplets slowly freeze, any air bubbles in the water escape—producing relatively bubble-free, clear ice. By contrast, in regions that have less moisture, the growth rate is slower, and less latent heat is released. The supercooled cloud droplets immediately freeze as they collide with the growing hailstone. The air bubbles are "frozen" in place, leaving milky ice—also referred to as *rime ice*.

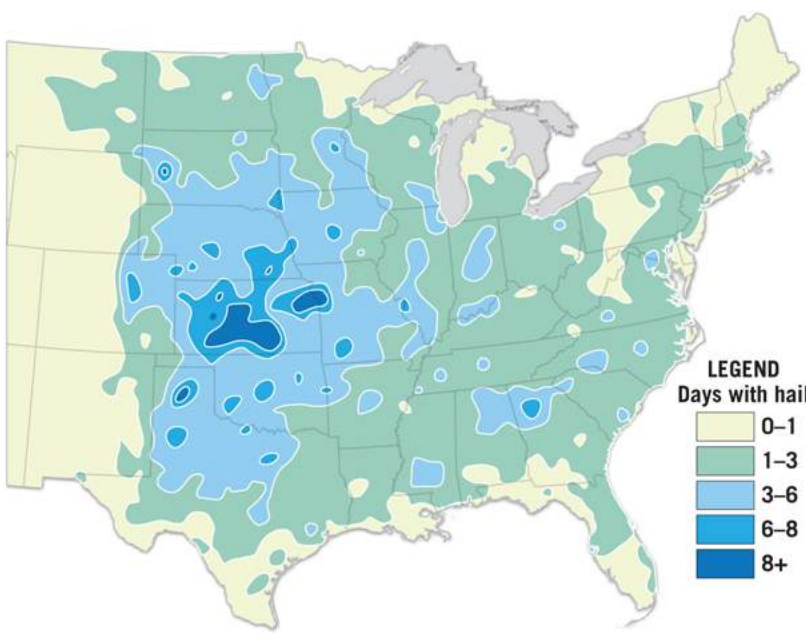
Most hailstones have diameters between 1 centimeter (pea size) and 5 centimeters (golf ball size), although some can be as big as softballs. Occasionally, hailstones weighing 1 pound or more have been reported; most of these are composites of several stones frozen together. These large hailstones have fall velocities that exceed 160 kilometers (100 miles) per hour.

The record for the largest hailstone ever found in the United States was set on July 23, 2010, in Vivian, South Dakota. The stone was over 20 centimeters (8 inches) in diameter and weighed nearly 900 grams (2 pounds). The stone that held the previous record of 766 grams (1.69 pounds) fell in Coffeyville, Kansas, in 1970 (Figure 5.22B). The diameter of the stone found in South Dakota also surpassed the previous record of a 17.8-centimeter (7-inch) stone that fell in Aurora, Nebraska, in 2003. Even larger hailstones have reportedly been recorded in Bangladesh, where a 1987 hailstorm killed more than 90 people.

The destructive effects of large hailstones are well known, especially to farmers whose crops have been devastated in a few minutes and to people whose windows, roofs, and cars have been damaged (Figure 5.23). In the United States, hail damage each year can run into the hundreds of millions of dollars. One of the costliest hailstorms to occur in North America took place June 11, 1990, in Denver, Colorado, with total damage estimated to exceed $625 million. Figure 5.24 shows the average number of hail occurrences per year over a 10-year period.

Figure 5.23 Parked cars with severe hail damage

Figure 5.24 Average number of hail reports per year over a 100-square-mile area during a 10-year period



Rime

Rime is a deposit of ice crystals formed by the freezing of supercooled fog or cloud droplets on objects whose surface temperature is below freezing. When rime forms on trees, it adorns them with its characteristic ice feathers, which can be spectacular to observe (Figure 5.25). In these situations, objects such as pine needles act as freezing nuclei, causing the supercooled droplets to freeze on contact. On occasions when the wind is blowing, only the windward surfaces of objects will accumulate the layer of rime.

Figure 5.25 Rime consists of delicate ice crystals

Rime forms when supercooled fog or cloud droplets freeze on contact with objects.

Concept Checks 5.5

■ Compare and contrast rain, drizzle, and mist.

■ Describe sleet and freezing rain. Why does freezing rain result on some occasions and sleet on others?

■ How does hail form? What factors govern the ultimate size of hailstones?

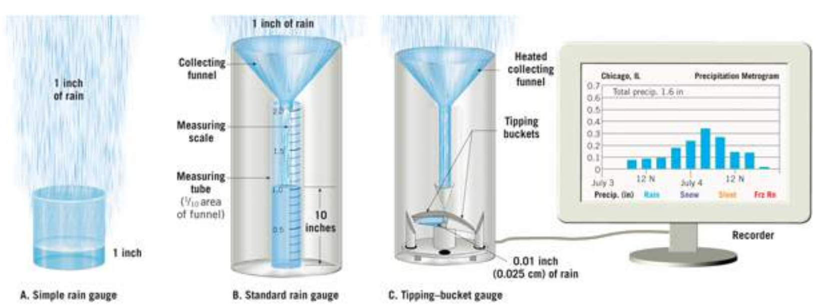
5.6 Precipitation Measurement

LO 6 Describe the instruments used to measure precipitation, including the standard rain gauge, snow pillow, and weather radar.

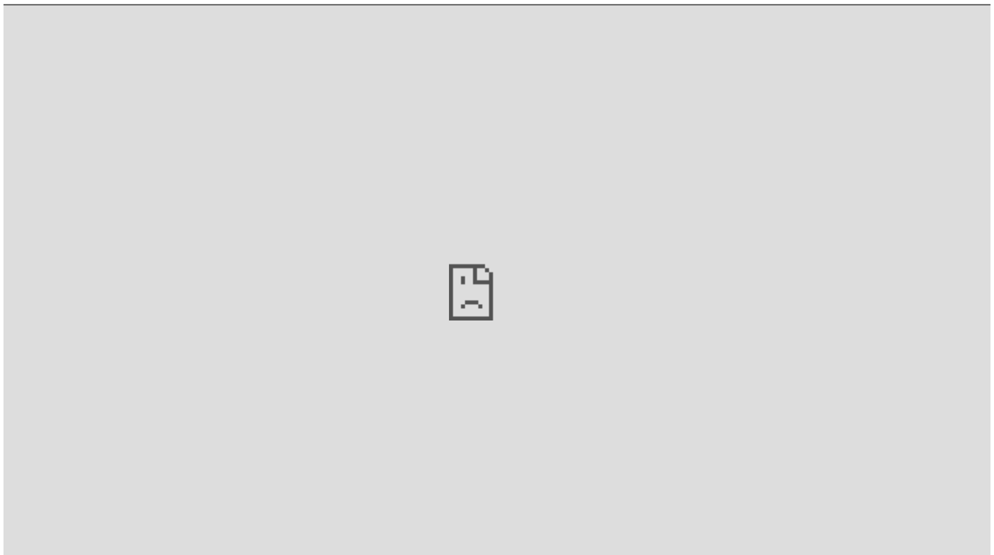
The most common form of precipitation, rain, is probably the easiest to measure. Any open container that has a consistent cross-section throughout can be a rain gauge (Figure 5.26A). In general practice, however, meteorologists use more sophisticated devices to measure small amounts of rainfall more accurately and to reduce loss from evaporation.

Figure 5.26 Precipitation measurement

A. The simplest gauge is any container left in the rain. **B.** The standard rain gauge increases the height of water collected by a factor of 10, allowing for accurate rainfall measurement to the nearest 0.025 centimeter (0.01 inch). Because the cross-sectional area of the measuring tube is only one-tenth as large as the collector, rainfall is magnified 10 times. **C.** The tipping-bucket rain gauge contains two "buckets," each holding the equivalent of 0.025 centimeter (0.01 inch) of liquid precipitation. When one bucket fills, it tips, and the other bucket takes its place. Each event is recorded as 0.01 inch of rainfall.



Watch **Video: Global Precipitation**



Measuring Rainfall

The **standard rain gauge** (Figure 5.26B) has a diameter of about 20 centimeters (8 inches) at the top. Once the water is caught, a funnel conducts the rain through a narrow opening into a cylindrical measuring tube that has a cross-sectional area only one-tenth as large as the receiver. Consequently, rainfall depth is magnified 10 times, which allows for accurate measurements to the nearest 0.025 centimeter (0.01 inch). When the amount of rain is less than 0.025 centimeter (0.01 inch), it is generally reported as being a **trace of precipitation**.

In addition to the standard rain gauge, several types of recording gauges are routinely used. These instruments not only record the amount of rain but also its time of occurrence and intensity (amount per unit of time). Two of the most common gauges are the tipping-bucket gauge and the weighing gauge.

As Figure 5.26C illustrates, the **tipping-bucket gauge** consists of two compartments, each capable of holding 0.025 centimeter (0.01 inch) of rain, situated at the base of a funnel. When one "bucket" fills, it tips and empties its water. Meanwhile, the other "bucket" takes its place at the mouth of the funnel. Each time a compartment tips, an electrical circuit is closed, and 0.025 centimeter (0.01 inch) of precipitation is automatically recorded on a graph.

A **weighing gauge** collects precipitation in a cylinder that rests on a spring balance. As the cylinder fills, the movement is transmitted to a pen that records the data.

All rain gauges are susceptible to inaccuracies. The tipping-bucket rain gauge is known to underestimate heavy rainfall by perhaps 25 percent because of the rainwater that is not collected during the tipping movement of the bucket. Also, wind can lead to measurement errors, by causing either too much or too little precipitation to enter the collecting container. In addition, because a rain gauge provides data for a specific location, the significant variations in the amount of precipitation that reaches the ground over a large area cannot be accurately estimated.

Measuring Snowfall

When snow records are kept (see Severe & Hazardous Weather Box 5.1), two measurements are normally used: depth and water equivalent. One way to measure the depth of snow is by using a calibrated stick. The actual measurement is not difficult, but choosing a representative spot can be. Even when winds are light or moderate, snow drifts freely. As a rule, it is best to take several measurements in an open place, away from trees and obstructions, and then average them. To obtain the water equivalent, samples may be melted and then weighed or measured as rain.

Severe & Hazardous Weather 5.1

Worst Winter Weather

Extremes, whether the *tallest* building or the *record low temperature* for a location, fascinate many people. When it comes to weather, some places take pride in claiming to have the worst winters on record. In fact, both Fraser, Colorado, and International Falls, Minnesota, have proclaimed themselves the “ice box of the nation.” Although Fraser recorded the lowest temperature for the 48 contiguous states 23 times in 1989, neighboring Gunnison, Colorado, recorded the lowest temperature 62 times, far more than any other location.

Such facts do not impress the residents of Hibbing, Minnesota, where the temperature dropped to –38°C (–37°F) during the first week of March 1989. But this is mild stuff, say the old-timers in Parshall, North Dakota, where the temperature fell to –51°C (–60°F) on February 15, 1936. Not to be left out, Browning, Montana, holds the record for the most dramatic 24-hour temperature drop. Here the temperature plummeted 56°C (100°F), from a cool 7°C (44°F) to a frosty –49°C (–56°F) during a January evening in 1916.

> Temperature extremes represent one aspect of winter weather; heavy snowfall is another.

Although impressive, extreme temperatures represent only one aspect of winter weather. What about snowfall (Figure 5.A)? Cooke City holds the seasonal snowfall record for Montana, with 1062 centimeters (418.1 inches) during the winter of 1977–1978. And cities like Sault Ste. Marie, Michigan, and Buffalo, New York, can accumulate several feet of snow in a single storm due to the legendary snowfalls associated with the Great Lakes. Even larger snowfalls occur in many sparsely inhabited mountainous areas.

Figure 5.A

A winter snowstorm of historic proportions struck Chicago, Illinois, on February 2, 2011.

Try telling residents of the eastern United States that heavy snowfall alone makes for the worst weather. A blizzard in March 1993 produced heavy snowfall along with hurricane-force winds and record low temperatures that immobilized much of the region from Alabama to the Maritime Provinces of eastern Canada. This event quickly earned the well-deserved title Storm of the Century.

Weather Safety

The National Weather Service (NWS) issues many different weather alerts to warn people of potential hazards. An *Advisory* is issued if the forecast indicates an inconvenience that could become hazardous. A *Watch* is issued when there is an increased risk for a hazardous weather, but the likelihood of occurrence, location, or timing is still uncertain. When a *Warning* is issued, hazardous weather is occurring or will occur shortly. A Warning indicates that the hazardous weather poses a threat to life or property. Here are the meanings of some common NWS alerts for winter weather events.

Winter Weather Advisory

An accumulation of snow, sleet, and/or ice that will cause an inconvenience.

Winter Storm Watch/Warning

Significant snow or sleet in a 12- to 24-hour period, and/or ice accumulation capable of causing damage to trees or powerlines, and/or a combination of wind with snow or ice that could threaten life or property.

Blizzard Warning

Snow and/or blowing snow that reduces visibility to ¼ mile or less for at least 3 hours and winds of at least 56 kilometers (35 miles) per hour. There are no temperature criteria for a blizzard.

Freezing Rain Advisory

Ice accumulation of ¼ inch or less that could be dangerous.

Ice Storm Warning

Ice accumulation of at least ¼ inch that will cause dangerous conditions for both drivers and pedestrians. Power lines and limbs will likely be damaged.

Wind Chill Advisory/Warning

A combination of low temperatures and high winds will cause dangerous conditions for those not dressed properly. A Wind Chill Warning is issued when conditions are life threatening and any exposed skin will freeze quickly.

Freeze Watch/Warning

Temperatures below freezing are expected over a large region. This warning is issued only during the growing season to warn farmers of impending crop loss.

Frost Advisory

This is issued when the low temperature will be near freezing on a clear, calm night. This alerts homeowners to bring in or cover outdoor plants.

Apply What You Know

1. Explain the difference between a Watch, a Warning, and an Advisory.

The quantity of water in a given volume of snow is not constant. You may have heard media weathercasters say, "Every 10 inches of snow equals 1 inch of rain." But the actual water content of snow may deviate widely from this figure. It may take as much as 30 inches of light and fluffy dry snow (30:1) or as little as 4 inches of wet snow (4:1) to produce 1 inch of water.

> When snow records are kept, two measurements are normally used: depth and water equivalent.

To measure the mountain snowpack, which produces 75 percent of the water supply for the western United States, automated weather stations employ **snow pillows** that have been installed at more than 600 sites. A snow pillow typically consists of two, three, or four large panels that measure the pressure exerted by the weight of snow that collects on them. Because snow pillows have large surface areas and measure the water equivalent of snow, they provide a good estimate of available water when the spring melt arrives.

Eye on the Atmosphere 5.3

This image shows a phenomenon called a *punch hole cloud* that was produced when a jet aircraft ascended through a cloud deck composed of supercooled water droplets. As the aircraft passed through the clouds, tiny particles in the jet engine exhaust interacted with some of the supercooled water droplets—which froze instantly. The white fuzzy area in the center of the image consists of large ice crystals that formed within the area of the cloud occupied by the punch hole and began to fall as precipitation.

Apply What You Know

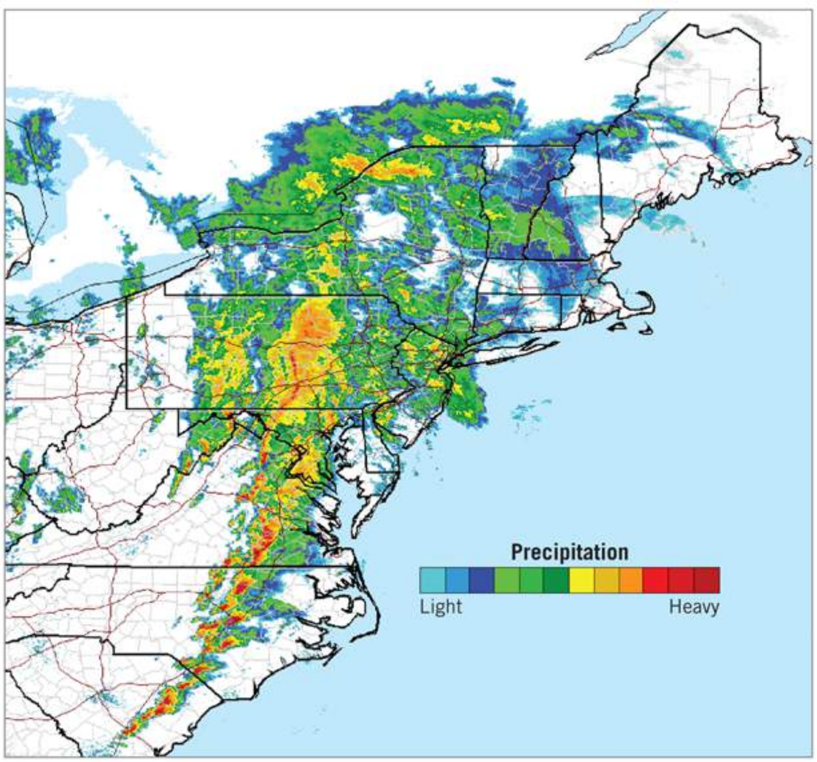
1. What is the name of the process whereby some cloud droplets freeze and grow at the expense of the remaining liquid cloud droplets?
2. Explain why only clouds composed of supercooled droplets can develop "punch holes."
3. Describe the role that a jet aircraft plays in the formation of punch hole clouds.

Precipitation Tracking by Weather Radar

Using **weather radar**, the National Weather Service (NWS) produces maps like the one in Figure 5.27, in which colors illustrate precipitation intensity. The development of weather radar has given meteorologists an important tool to track storm systems and the precipitation patterns they produce, even when the storms are as far away as a few hundred kilometers.

Figure 5.27 Doppler radar display produced by the National Weather Service

Colors indicate different intensities of precipitation. Note the band of heavy precipitation along the U.S. Eastern Seaboard.



Radar units have transmitters that send out short pulses of radio waves. The specific wavelengths selected depend on the objects being detected. When radar is used to monitor precipitation, wavelengths between 3 and 10 centimeters are employed. At these wavelengths, radio waves can penetrate clouds composed of small droplets, but they are reflected by larger raindrops, ice crystals, and hailstones. The echo intensity, called *radar reflectivity*, is converted to decibels (dBz) and displayed on a map. Because the echo is more intense when more precipitation is present, modern weather radar can depict both the rate of precipitation and its regional extent. Also, because the measurements are in real time, they are particularly useful in short-term forecasting.

> Weather radar is used to track the location and intensity of precipitation.

Despite its usefulness, weather radar does not always show what is occurring at Earth's surface. In order to avoid "ground clutter" such as trees and buildings, the radar signal is directed slightly upward at an angle. As a result, radar detects only precipitation very high up at locations far from the radar unit. For example, radar may detect precipitation high in the atmosphere that doesn't reach the surface (virga), or it may miss precipitation actually hitting the ground from low clouds. Occasionally, a radar unit will receive echoes produced by dense swarms of insects or birds. In addition, conventional radar systems cannot distinguish rain (liquid water) from solid forms of precipitation. Fortunately, the National Weather Service has upgraded most of its local forecast centers to *dual polarization radar*, which transmits both horizontal and vertical pulses and gathers significantly more data. This information helps forecasters distinguish rain, hail, snow, or sleet from other flying objects, including tornado debris.

Watch **Video: Record-Breaking Hailstorm as Seen By Radar**

Concept Checks 5.6

- Although any open container can serve as a rain gauge, what advantages does a standard rain gauge provide?
- Why is it important to collect both snow depth and water content?
- Why is weather radar useful in detecting precipitation?

5.7 Planned and Inadvertent Weather Modification

LO 7 Discuss several ways that humans attempt to modify the weather.

People modify the weather deliberately as well as unintentionally. Efforts to enhance precipitation at ski resorts and to dissipate fog at some airports illustrate planned intervention. One example of inadvertent weather modification is the increase in cloudiness from condensation trails produce by jet aircraft.

Planned Weather Modification

Planned weather modification is deliberate human intervention to influence atmospheric processes that constitute the weather—that is, to alter the weather for human purposes. The desire to change or enhance certain weather phenomena dates back to ancient history, when people used prayer, wizardry, dances, and even black magic in attempts to alter the weather.

Snow and Rain Making

The first breakthrough in weather modification came in 1946, when Vincent J. Schaefer discovered that dry ice, dropped into a supercooled cloud, spurred the growth of ice crystals. Once ice crystals form in a cloud of supercooled droplets, they grow larger (at the expense of the remaining liquid cloud droplets) and, upon reaching a sufficient size, fall as precipitation.

Scientists later learned that silver iodide crystals could also be used for **cloud seeding**. Unlike dry ice, which simply chills the air, silver iodide crystals act as freezing nuclei for the supercooled droplets—that is, liquid droplets with temperatures below 0°C (32°F). Because silver iodide can be easily delivered to clouds from burners on the ground or from aircraft, it is a more cost-effective alternative than dry ice (Figure 5.28).

Figure 5.28 **Cloud seeding**

Cessna aircraft equipped with silver iodide flares supply freezing nuclei to supercooled clouds in order to trigger precipitation.

Seeding of winter clouds that form along mountain barriers (orographic clouds) has been attempted on numerous occasions. Since 1977, Colorado's Vail and Beaver Creek ski areas have used this method to increase winter snows. An additional benefit of cloud seeding is that the increased precipitation, which melts and runs off during spring and summer months, can be collected in reservoirs for irrigation and hydroelectric power generation.

In recent years, the seeding of warm convective clouds with hygroscopic (water-seeking) particles has received renewed attention. The interest in this technique arose when it was discovered that a pollution-belching paper mill near Nelspruit, South Africa, seemed to be triggering precipitation. Research aircraft flying through clouds near the paper mill collected samples of the particulate matter emitted from the mill. It turned out that the mill was emitting tiny salt crystals (potassium chloride and sodium chloride), which rose into the clouds. Because these salts attract moisture, they quickly form large cloud droplets, which grow into raindrops through the collision–coalescence process. Thus, seeding of warm clouds using hygroscopic particles seems to show promise for accelerating the precipitation process.

> Planned weather modification is deliberate human intervention to influence atmospheric processes that constitute the weather.

Researchers estimate a 10 percent increase in snowfall from clouds seeded with silver iodide compared to those left unseeded. Because cloud seeding has shown some promising results and is relatively inexpensive, it has been a primary focus of modern weather-modification technology.

Fog and Stratus Cloud Dispersal

One of the most successful applications of cloud seeding involves spreading dry ice (solid carbon dioxide) into layers of supercooled fog or stratus clouds to disperse them and thereby improve visibility. Airports, harbors, and foggy stretches of interstate highway are obvious candidates. Such applications trigger a transformation in cloud composition from supercooled water droplets to ice crystals. The ice crystals then settle out, leaving an opening in the cloud or fog. Commercial airlines have used this method at selected foggy airports in the western United States.

Unfortunately, most fog does not consist of supercooled water droplets. The more common "warm fogs" are more expensive to combat because seeding will not diminish them. Successful attempts at dispersing warm fogs have involved mixing drier air from above into the fog. When the layer of fog is very shallow, helicopters have been used. By flying just above the fog, the helicopter creates a strong downdraft that forces drier air toward the surface, where it mixes with the saturated foggy air.

Hail Suppression

Each year, hailstorms inflict on average $500 million in property damage and crop loss in the United States (Figure 5.29). Occasionally a single severe hailstorm can produce damages that exceed that amount. As a result, some of history's most interesting efforts at weather modification have focused on hail suppression.

Figure 5.29 **Hail damage to fruit**

Farmers desperate to find ways to save their crops have long believed that strong noises—explosions, cannon shots, or ringing church bells—can help reduce the amount of hail produced during a thunderstorm. In Europe, it was once common practice for village priests to ring church bells to shield nearby farms from hail.

Modern attempts at hail suppression use various methods of cloud seeding using silver iodide crystals to disrupt the growth of hailstones. In an effort to verify the effectiveness of cloud seeding as a means to suppress hail, the U.S. government established the National Hail

Research Experiment in northeastern Colorado. This effort included several randomized cloud-seeding experiments. An analysis of the data collected after 3 years revealed no statistically significant difference in the occurrence of hail between the seeded and unseeded clouds, so the planned 5-year experiment was abandoned. Nevertheless, cloud seeding is still employed today in an attempt to prevent hail, and research on hail suppression continues.

Frost Prevention

A **frost, or freeze hazard**, is a strictly temperature-dependent phenomenon that occurs when the air temperature falls to 0°C (32°F) or below, killing flowers and produce. The word *frost* is commonly used for ice crystals that form on surfaces near the ground during the night. According to the World Meteorological Organization, the correct term for the deposits of ice crystals are *hoar frost* or *white frost*, which form only when air becomes saturated at subfreezing temperatures.

A frost, or freeze hazard, can be generated in two ways: when a cold air mass moves into a region or when sufficient radiation cooling occurs on a clear night. Frost associated with an invasion of cold air, which can produce widespread crop damage, is characterized by low daytime temperatures and long periods of freezing conditions. By contrast, frost induced by radiation cooling is strictly a nighttime phenomenon that tends to be confined to low-lying areas. Obviously, the latter phenomenon is much easier to combat.

Several methods of frost prevention are being used with varying success. They either conserve heat (reduce heat loss at night) or add heat to warm the lowermost layer of air.

Heat-conservation methods include covering plants with insulating material, such as paper or cloth, and generating particles that, when suspended in air, reduce the rate of radiation cooling. Warming methods employ *water sprinklers*, *air-mixing techniques*, and/or *orchard heaters*. Water sprinklers (Figure 5.30) add heat in two ways: first, from the warmth of the water and, more importantly, from the latent heat of fusion released when the water freezes. As long as an ice–water mixture remains on the plants, the latent heat released will keep the temperature from dropping below 0°C (32°F).

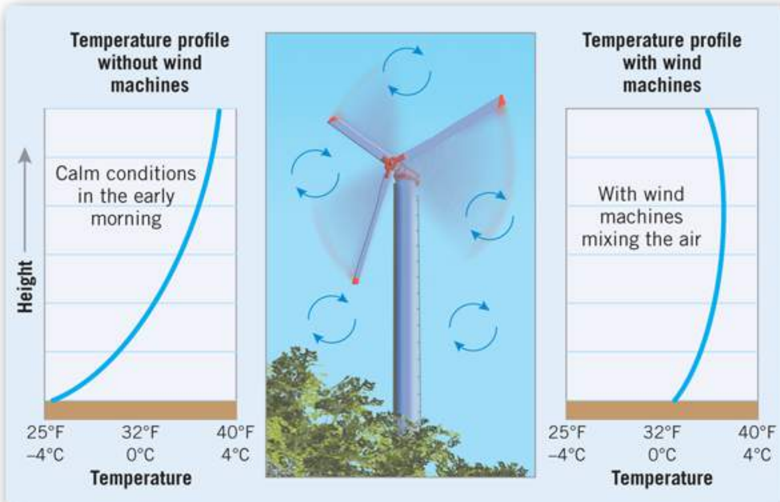
Figure 5.30 A common frost-prevention method

Sprinklers distribute water, which releases latent heat as it freezes on citrus.

> Methods of frost prevention include conserving heat (reduce heat loss at night) or adding heat to warm the lowermost layer of air.

Air mixing works best when the air temperature 15 meters (50 feet) above the ground is at least 5°C (9°F) warmer than the surface temperature. Through use of a wind machine, the warmer air aloft is mixed with the colder surface air (Figure 5.31).

Figure 5.31 Wind machines mix warmer air aloft with cooler surface air to help prevent frost damage



Orchard heaters probably produce the most successful results. However, because as many as 30 to 40 heaters are required per acre, fuel costs and pollution emissions are significant.

Inadvertent Weather Modification

The effects of *inadvertent*, or *unintentional*, *weather modification* are numerous, and scientists are beginning to understand them better. Unintentional weather modifications affect cloud formation and precipitation patterns. Changes in air quality, visibility, and the formation of acid rain caused by human activity are covered in Chapter 13, while human impacts on global climate are a major topic in Chapter 14. In addition, human effects on city temperatures, known as the "urban heat island," are discussed in Chapter 3.

Effects of Large Transportation Corridors

You have undoubtedly seen *contrails* (from *condensation trail*) in the wake of an aircraft flying on a clear day. Contrails, which are simply human-made clouds, form because jet aircraft engines expel large quantities of hot, moist air. Upon mixing with the frigid air aloft, the moist air cools sufficiently to reach saturation.

Contrails typically form above 9 kilometers (6 miles), where air temperatures are a frigid −50°C (−58°F) or colder. Thus, it is not surprising that contrails are composed of minute ice crystals. Most contrails have a very short life span. Once formed, these streamlined clouds mix with surrounding cold, dry air and ultimately sublimate. However, if the air aloft is near saturation, contrails may survive for long periods. Under these conditions, the upper airflow usually spreads these narrow clouds into broad bands of cirrus or cirrostratus clouds. Similar increases in cloud cover have also been detected recently along major air transport routes.

With the increase in air traffic over the past few decades, an overall increase in cloudiness has been recorded, particularly near major transportation hubs (Figure 5.32). It appears these human-made clouds reduce the amount of incoming solar radiation reaching the ground and can lead to lower daytime maximum temperatures. Because cloud cover also reduces the amount of radiation cooling that occurs at night, additional research is needed to accurately determine the impact of contrails on climate change.

Figure 5.32 Inadvertent increase in cloud cover caused by contrails

These "artificial clouds" cover an increasing percentage of the planet's surface, and the percentages are far higher in places such as southern California and some parts of Europe.

Urban Effects

Major population centers enhance the formation of warm clouds and increase precipitation in these urban areas by as much as 20 percent. This effect does not appear to alter winter precipitation patterns.

Increased industrialization associated with urbanization also influences weather conditions downwind of major cities. The added particulates and aerosols from industry and transportation sectors reduce air quality and visibility and also contribute to increased cloudiness and precipitation. In addition, large cooling lakes adjacent to industrial facilities—used to dispose of hot water that was heated during manufacturing—have been shown to cause localized fog, low clouds, and even icing in the winter.

> Major population centers enhance the formation of warm clouds and increase precipitation in these urban areas by as much as 20 percent.

Concept Checks 5.7

- What atmospheric condition must exist for cloud seeding to work?
- What are some strategies used to reduce fog? Hail? Frost?
- Describe two inadvertent weather modifications.

Concepts in Review

5.1 Cloud Formation

LO 1 Explain the roles of adiabatic cooling and cloud condensation nuclei in cloud formation.

Key Terms

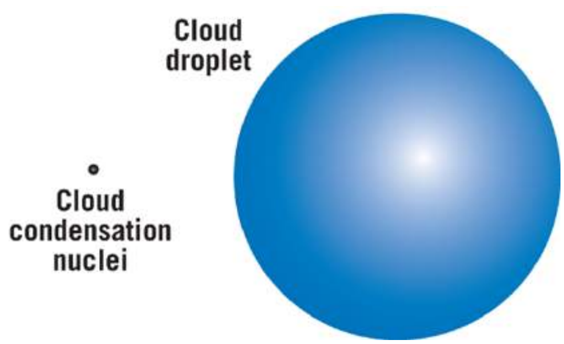
cloud

cloud condensation nuclei

hygroscopic (water-seeking) nuclei

hydrophobic (water-repelling) nuclei

- Clouds form in the atmosphere when water vapor condenses on cloud condensation nuclei. This produces tiny cloud droplets held aloft by the slightest updrafts.
- Clouds, visible aggregates of minute droplets of water and/or tiny crystals of ice, are one form of condensation.



5.2 Cloud Classification

LO 2 Name and describe the 10 basic cloud types, based on form and height. Contrast nimbostratus and cumulonimbus clouds and their associated weather.

Key Terms

nimbus

high cloud

middle cloud

low cloud

clouds of vertical development

cirrus

cirrocumulus

cirrostratus

altocumulus

altostratus

stratus

stratocumulus

nimbostratus

clouds of vertical development

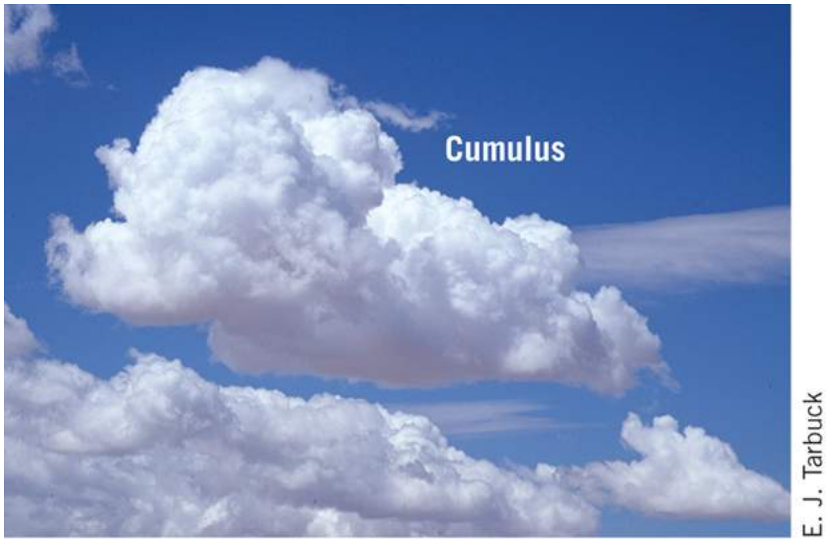
cumulus

cumulonimbus

lenticular clouds

- Clouds are classified based on two criteria: form and height. The three basic cloud forms are cirrus (high, white, and thin), cumulus (globular, individual cloud masses), and stratus (sheets or layers).
- Cloud heights can be high, with bases above 6000 meters (20,000 feet); middle, from 2000 to 6000 meters; or low, below 2000 meters (6500 feet). Clouds of vertical development have bases in the low height range and extend upward into the middle or high range.

- Considering both form and height, 10 basic cloud types can be classified.



5.3 Types of Fog

LO 3 Identify the basic types of fog and describe how each forms.

Key Terms

fog

radiation fog

advection fog

upslope fog

steam fog

frontal (precipitation) fog

- Fog, generally considered an atmospheric hazard, is a cloud with its base at or very near the ground.
- Fogs formed by cooling include radiation fog, advection fog, and upslope fog. Fogs formed by the addition of water vapor are steam fog and frontal fog.

5.4 How Precipitation Forms

LO 4 Describe the Bergeron process and explain how it differs from the collision–coalescence process.

Key Terms

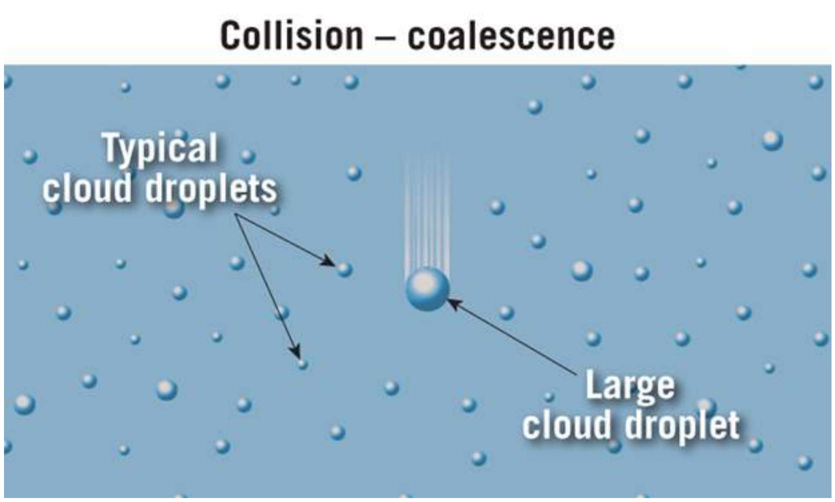
Bergeron process

supercooled water

freezing nucleus

collision–coalescence process

- For precipitation to form, millions of cloud droplets must coalesce into drops large enough to sustain themselves during their descent.
- Two mechanisms have been proposed to explain the formation of precipitation. They are the Bergeron process, which produces precipitation from cold clouds, and the warm-cloud process called the collision–coalescence process.



5.5 Forms of Precipitation

LO 5 Describe the atmospheric conditions that produce rain, snow, sleet, freezing rain, and hail.

Key Terms

rain

virga

fallstreaks

drizzle

mist

snow

graupel

sleet

freezing rain (glaze)

hail

rime

- The two most common and familiar forms of precipitation are rain and snow.
- Sleet forms when raindrops freeze while falling through a thick layer of subfreezing air. Freezing rain results when supercooled raindrops freeze upon contact with cold objects.
- Hail is produced in towering cumulonimbus clouds.

Nicolas Perrault

5.6 Precipitation Measurement

LO 6 Describe the instruments used to measure precipitation, including the standard rain gauge, snow pillow, and weather radar.

Key Terms

standard rain gauge

trace of precipitation

tipping-bucket gauge

weighing gauge

snow pillow

weather radar

- The instruments most commonly used to measure rain are the standard rain gauge, which is read directly, and the tipping-bucket gauge and the weighing gauge, which record the amount and intensity of rain. The two most common measurements of snow are depth and water equivalent.
- Weather radar gives meteorologists an important tool to track storm systems and the precipitation patterns they produce, even when the storms are as far away as a few hundred kilometers.

5.7 Planned and Inadvertent Weather Modification

LO 7 Discuss several ways that humans attempt to modify the weather.

Key Terms

cloud seeding

frost (freeze hazard)

- Planned weather modification is deliberate human intervention to influence atmospheric processes that constitute the weather.
- The effects of inadvertent or unintentional weather modification include increased cloudiness, which may lower surface temperatures, and an increase in precipitation.

Exercises and Online Activities

Mastering Meteorology™

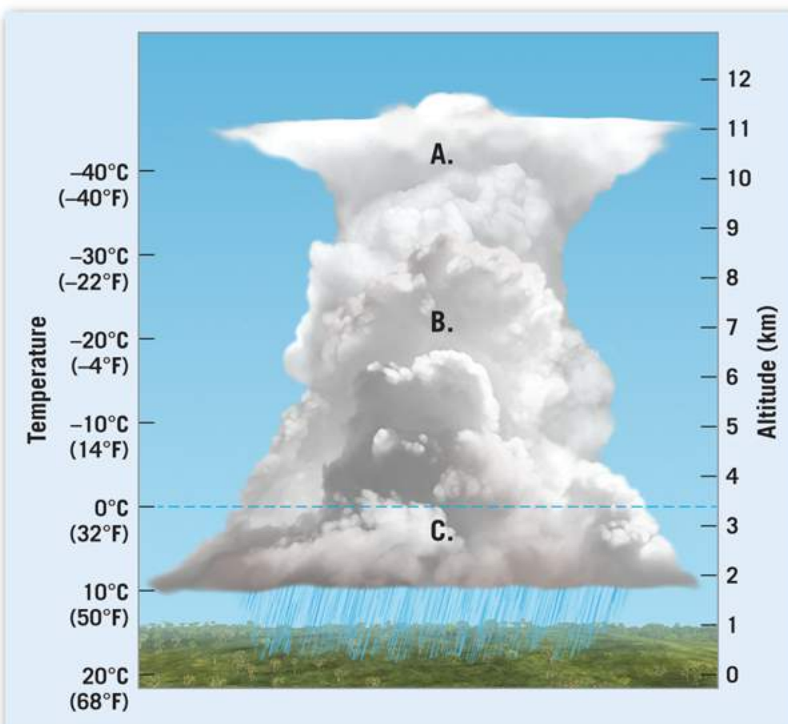
For instructor-assigned homework, test prep resources, and other learning materials, visit **Mastering Meteorology.**

Review Questions

1. What are condensation nuclei, and why are they required to produce clouds?
2. Categorize the 10 basic cloud types by form, then by height.
3. How is fog similar to a cloud? How is it different?
4. Why is dense fog common along the Pacific coast?
5. Define *supersaturation*.
6. How does precipitation form in cold clouds?
7. Name and describe the mechanism by which precipitation forms in warm clouds.
8. How does snow form? How is it different from rain formation?
9. Contrast the atmospheric and surface conditions required for sleet and for freezing rain.
10. What cloud type produces hail? Describe the two methods by which hailstones form.
11. What is rime?
12. Describe the various gauges used to measure rainfall.
13. What is a snow pillow, and why is it more useful than measuring inches of snow?
14. Explain how radar is used to monitor precipitation.
15. How can weather be modified to produce more rain or snow? Disperse fog? Suppress hail? Prevent frost?
16. What are contrails, and why do they occur? How do contrails affect local weather?

Give It Some Thought

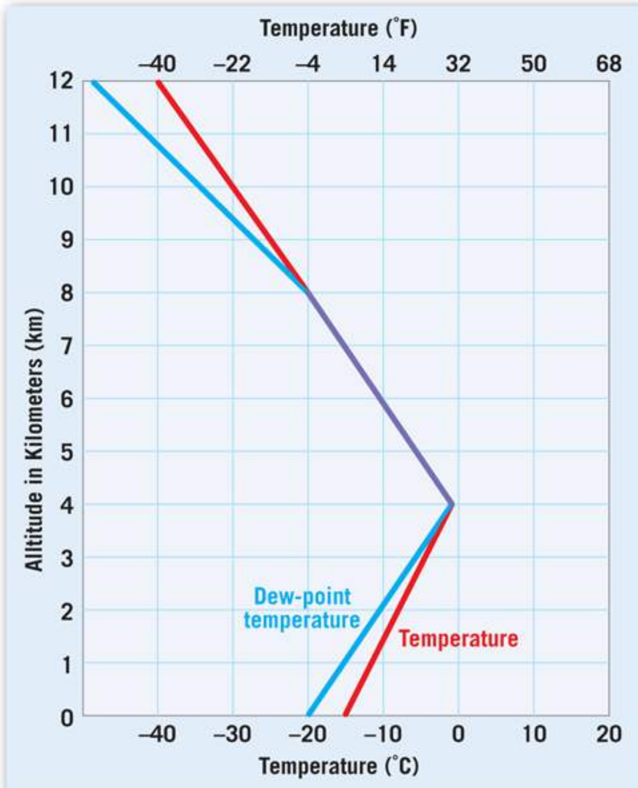
1. Clouds are classified into four major height categories: low, middle, high, and clouds of vertical development. Explain why low clouds (or clouds of vertical development) are much more likely to produce precipitation than middle or high clouds.
2. Name the cloud types associated with the following characteristics:
   a. Halos
   b. Light to moderate precipitation
   c. Hail
   d. Mackerel sky
   e. Mares′ tails
3. Use the accompanying diagram, which shows a towering cumulonimbus cloud and the temperature profile of the atmosphere, to complete the following:



a. What is the temperature at the base of this cloud?
b. At point A, would the cloud consist of liquid droplets only, ice crystals only, or both liquid droplets and ice crystals?
c. At point B, would the cloud consist of liquid droplets only, ice crystals only, or both liquid droplets and ice crystals?
d. At point C, would the cloud consist of liquid droplets only, ice crystals only, or both liquid droplets and ice crystals?

4. Fog can be defined as a cloud with its base at or very near the ground, yet fogs and clouds form by different processes. Describe the similarities and differences in the formation of fogs and clouds.
5. Why does radiation fog form mainly on clear nights as opposed to cloudy nights?
6. Assume that it is a midwinter day in central Illinois. Mild conditions prevail because of a steady wind from the south. As the day progresses, fog forms across a broad area. Identify the likely type of fog.
7. Imagine you are driving in a hilly area early in the morning and encounter fog as you descend into the valleys, but as you drive out of the valleys, the conditions clear. Identify the likely type of fog.
8. Describe or sketch the vertical temperature profile that would cause precipitation that began as snow to reach the ground as each of the following:
   a. Snow
   b. Rain
   c. Freezing rain
9. Use the accompanying diagram, which shows changes in temperature and the dew-point temperature with altitudes, to

complete the following. (Recall from Chapter 4 that the dew point is the temperature at which the air reaches saturation.)



a. At what altitude would clouds be found: 0–4 kilometers, 4–8 kilometers, or 8–12 kilometers?

b. What would this cloud consist of: liquid droplets only, ice crystals only, or both liquid droplets and ice crystals?

c. If this cloud produced precipitation, what type would likely reach Earth's surface: rain, snow, sleet, or freezing rain?

10. Why is it unlikely for virga and fog to occur simultaneously?

11. The accompanying images show two different types of precipitation after they have been deposited.

A. B. E. J. Tarbuck

a. Name the types of precipitation shown.

b. Describe the nature (form) of each type of precipitation before it was deposited.

c. What characteristic do these two types of precipitation have in common?

d. In what way are they different?

12. Weather radar provides information on the intensity as well as the total amount of precipitation. Table A shows the relationship between radar reflectivity values and rainfall rates. If radar measured a reflectivity value of 47 dBZ for 2½ hours at a particular location, how much rain has fallen there?

Table A
Conversion of radar reflectivity to rainfall rate

Radar Reflectivity (dBZ)	Rainfall Rate (inches/hr)
65	16+
60	8.0
55	4.0
52	2.5
47	1.3
41	0.5
36	0.3
30	0.1
20	trace

By the Numbers

1. **1.** Suppose the air temperature is 20°C (68°F), and the relative humidity is 50 percent at 6:00 P.M. Also suppose that during the evening, the air temperature drops, but its water vapor content does not change. If the air temperature drops 1°C (1.8°F) every 2 hours, will fog occur by sunrise (6:00 A.M.) the next morning? Explain your answer. (*Hint:* The data you need are found in Table 4.1.)
2. **2.** Under the same conditions as in Problem 1, will fog occur if the air temperature drops 1°C (1.8°F) every hour? If so, when will it first appear? What name is given to fog of this type that forms because of surface cooling during the night?
3. **3.** Assuming that the air is still, how long would it take a large raindrop (5 mm) to reach the ground if it fell from a cloud base at 3000 meters? (See Table 5.4.) How long would a typical raindrop (2 mm) take to fall to the ground from the same cloud? How long if it were a drizzle drop (0.5 mm)?
4. **4.** Assuming that the air is still, how long would it take for a typical cloud droplet (0.02 mm) to reach the ground if it fell from a cloud base at 1000 meters? (See Table 5.4.) Explain why it is very unlikely that a cloud droplet would ever reach the ground, even if the air were perfectly still.
5. **5.** The record for the largest hailstone in the United States was set on July 23, 2010, in Vivian, South Dakota. It was 8 inches in diameter and 18.62 inches in circumference, and it weighed nearly 2 pounds. The maximum fall speed of a spherical hailstone of diameter d can be calculated using $V = k2d$, where $k = 20$ if d is in centimeters and V is in meters per second. Estimate the strength (speed) of the updrafts in this storm that were necessary to support the stone just before it began to fall. Convert your

answer from meters per second to feet per second and then to miles per hour.

6. The dimensions of the large cumulonimbus cloud pictured are roughly 12 kilometers high, 8 kilometers wide, and 8 kilometers long. Assume that the droplets in every 1 cubic meter of the cloud total 0.5 cubic centimeter of water. How much liquid water does the cloud contain? How many gallons does it contain (3785 cm^3 = 1 gallon)?

Beyond the Textbook

1. Types of Precipitation

Go to www.youtube.com and find at least one video for each of these precipitation types: **(1) hail, (2) freezing rain, (3) sleet, (4) rain, (5) snow**. As you watch the video, write down a short synopsis (three to four sentences long) of what happens in the video. Copy and paste the URLs of the videos you viewed, along with your video summaries, onto a Word document for your instructor—all your information should be in *one* document.

2. Identifying Cloud Types from Photographs

Part A. Go to http://cloudappreciationsociety.org and find at least one photo example of each cloud type listed below. You can find images of specific cloud types by clicking on the Cloud Photo Gallery button and then clicking on the image gallery icon, located near the top right. (*Note:* Search for one cloud type at a time by re-clicking to remove the previous cloud selections.) Scroll through a few pictures to find an example(s) that is somewhat similar to the ones in Figures 5.2 through 5.7. Copy the picture by right-clicking on the image and choosing Copy Image. Then paste it into a Word document, along with the description and photographer information.

Cloud types:

1. **cirrus,**
2. **cirrocumulus,**
3. **cirrostratus,**
4. **altocumulus,**
5. **altostratus,**
6. **stratocumulus,**

7. **nimbostratus,**
8. **cumulus,**
9. **cumulonimbus.**

Part B. In addition to the standard cloud types listed above, find images of at least six other types of clouds from the list below. Search online to determine how each of the six clouds you chose is formed. For these clouds, obtain a photograph, description, and photographer information, and a brief (one to two sentences) description of how the cloud is formed.

Cloud types:

1. **cap cloud,**
2. **mammatus (mamma),**
3. **lenticularis,**
4. **contrail,**
5. **Kelvin-Helmholtz,**
6. **nacreous,**
7. **noctilucent,**
8. **roll cloud,**
9. **pyrocumulus.**

Chapter 6 Air Pressure and Winds

Kite surfing at the beach of Los Lances, Spain.

Focus on Concepts

Each statement represents the primary learning objective for the corresponding major heading within the chapter. After you complete the chapter, you should be able to:

1. Define *atmospheric pressure* and explain how it is displayed on a weather map (6.1).
2. Identify the factors affecting air pressure at Earth's surface as well as aloft (6.2).
3. List and describe the three forces that act on the atmosphere to either create or alter winds (6.3).
4. Explain why winds aloft flow roughly parallel to the isobars, whereas surface winds travel at an angle across the isobars (6.4).
5. Sketch a diagram of the airflow around a low-pressure center (cyclone) and a high-pressure center (anticyclone), and describe the weather associated with each (6.5).
6. Define *prevailing wind* and explain how wind direction is expressed (6.6).

Of the various elements of weather and climate, changes in air pressure are the least perceptible to humans; however, they are very important in producing changes in our weather because variations in air pressure generate winds that trigger changes in temperature and humidity. In addition, air pressure is a significant factor in weather forecasting and is closely tied to the other elements of weather (temperature, moisture, and wind) in cause-and-effect relationships. For example, horizontal differences in air pressure create the winds illustrated in the chapter-opening photo.

6.1 Atmospheric Pressure and Wind

LO 1 Define *atmospheric pressure* and explain how it is displayed on a weather map.

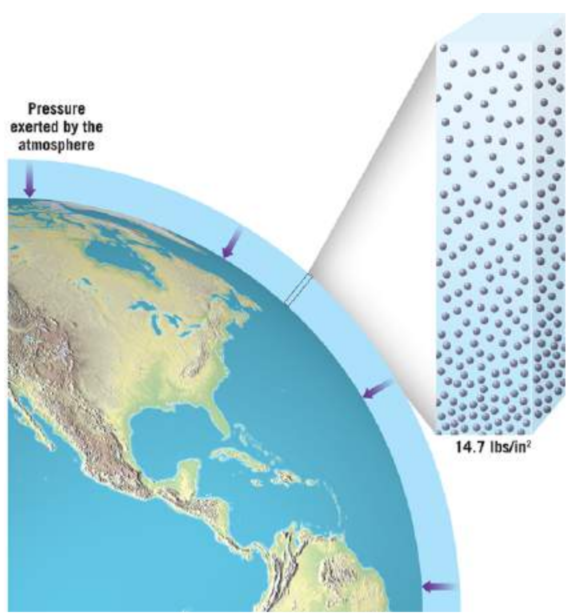
We know that air moves *vertically* if it is forced over a barrier or if it is warmer and thus more buoyant than surrounding air. But what causes air to move *horizontally*—the phenomenon we call **wind**? Simply stated, *wind is the result of horizontal differences in atmospheric pressure*. Air flows from areas of *higher pressure* to areas of *lower pressure*. You may have experienced this phenomenon when opening a can of warm carbonated soda. When you open the can, the gaseous carbon dioxide that was dissolved in the liquid rushes from the area of higher pressure inside the can to the area of lower pressure outside. Wind is nature's attempt to balance inequalities in air pressure.

What Is Atmospheric Pressure?

We live at the bottom of the atmosphere and, just as the creatures living at the bottom of the ocean are subjected to pressure exerted by water, humans are subjected to the pressure exerted by the weight of the atmosphere above. Although we do not generally notice the pressure exerted by the ocean of air around us (except when rapidly ascending or descending in an elevator or airplane), it is nonetheless substantial.

We define **atmospheric pressure**, or simply **air pressure**, as the force per unit area on a surface exerted by the weight of the air above. Average atmospheric pressure at sea level is about 14.7 pounds per square inch (equivalent to 1 kilogram per square centimeter in the metric system). Specifically, a column of air 1 square inch in cross section, measured from sea level to the top of the atmosphere, would weigh about 14.7 pounds (Figure 6.1). This is roughly the same pressure produced by a 1-square-inch column of water 10 meters (33 feet) in height.

Figure 6.1 Average air pressure at sea level is about 14.7 pounds per square inch



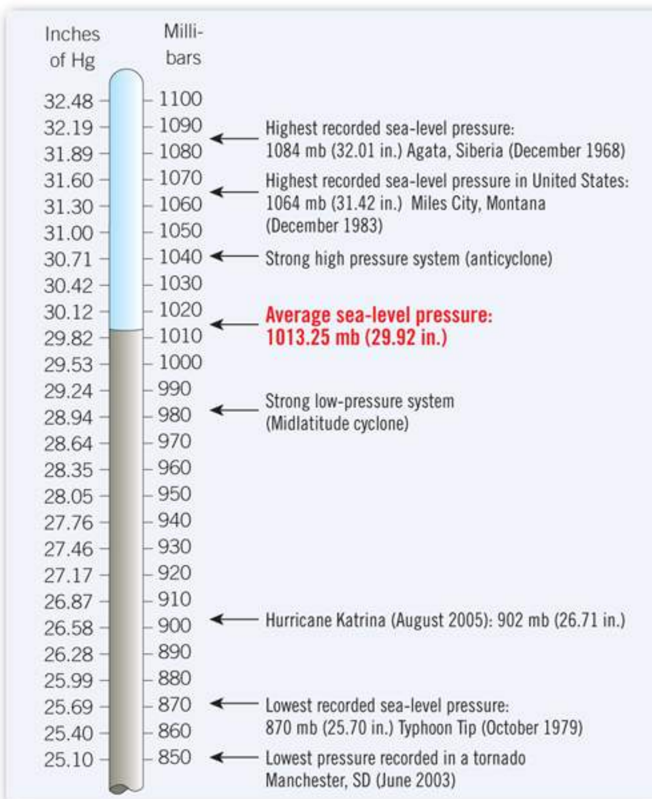
> Atmospheric pressure is the weight of the air above a location.

The pressure that air exerts at Earth's surface is much greater than most people realize. For example, the air pressure exerted on the top of a small (50-centimeter-by-100-centimeter) school desk exceeds 5000 kilograms (11,000 pounds), or about the weight of a 50-passenger school bus. Why doesn't the desk collapse under the weight of the air above? Simply, air pressure is exerted in all directions—down, up, and sideways. Thus, the air pressure around all sides of the desk is exactly balanced.

Measuring Atmospheric Pressure

To describe atmospheric pressure, the National Weather Service (NWS) uses a unit called the *pascal* (newton per square meter). Under conditions typically found at sea level, the atmosphere exerts a pressure of 101,325 pascals. To simplify this large number, the NWS adopted the **millibar (mb)**, which equals 100 pascals, as the unit used on surface weather maps. Thus, average **sea-level pressure** is 1013.25 millibars (Figure 6.2).

Smartfigure 6.2 A comparison of atmospheric pressure in inches of mercury and in millibars



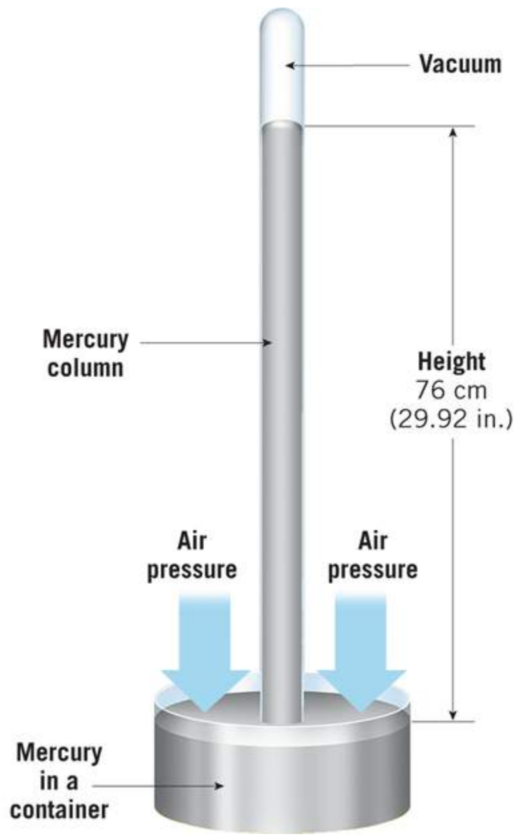
Watch **SmartFigure: Air Pressure**

> The National Weather Service uses millibars (mb) to indicate atmospheric pressure on weather maps.

You may have heard the expression "inches of mercury," which is also used to describe atmospheric pressure. This expression dates from 1643, when Torricelli, a student of the famous Italian scientist Galileo, invented the **mercury barometer**. Torricelli correctly described the atmosphere as a vast ocean of air that exerts pressure on Earth's surface. To measure this force, he closed one end of a glass tube and filled it with mercury, then inverted the tube into a dish of mercury (Figure 6.3). Torricelli found that the mercury flowed out of the tube until the weight of the mercury column was balanced by the pressure exerted on the surface of the mercury by the air above. In other words, the weight of the mercury in the column equaled the weight of a similar-diameter column of air that extended from the ground to the top of the atmosphere.

Figure 6.3 Mercury barometer

The weight of the column of mercury is balanced by the pressure exerted on the dish of mercury by the air above. If the pressure decreases, the column of mercury falls; if the pressure increases, the column rises.



Torricelli noted that when air pressure increases, the mercury in the tube rises; conversely, when air pressure decreases, so does the height of the column of mercury. The height of the column of mercury, therefore, became the measure of the air pressure—in inches of mercury. With some refinements, Torricelli's mercury barometer remains the standard pressure-measuring instrument. Because air pressure is measured with a barometer, it is also commonly called **barometric pressure**.

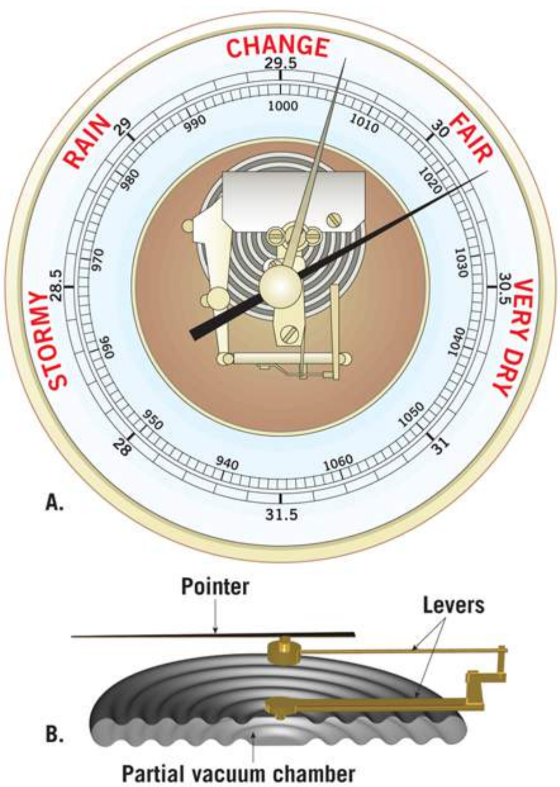
Standard atmospheric pressure at sea level equals 29.92 inches (760 millimeters) of mercury. The National Weather Service uses millibars on

U.S. weather maps and charts but reports surface pressure to the public in inches of mercury.

The need for a smaller, more portable instrument for measuring atmospheric pressure led to the development of the **aneroid barometer** (*aneroid* means "without liquid"; Figure 6.4A). Rather than using mercury, the aneroid barometer uses a partially evacuated metal chamber (Figure 6.4B). The chamber, being sensitive to pressure variations, compresses as pressure increases and expands as pressure decreases.

Figure 6.4 **Aneroid barometer**

A. Illustration of an aneroid barometer. **B.** The aneroid barometer has a partially evacuated chamber that changes shape, compressing as atmospheric pressure increases and expanding as pressure decreases.



As shown in Figure 6.4A, the face of an aneroid barometer intended for home use includes the words *fair*, *change*, *rain*, and *stormy*. Notice that "fair weather" corresponds with high-pressure readings, whereas "rain" is associated with low pressures. To *predict* weather in a local area, the change in air pressure over the past few hours is more important than the current pressure reading. Falling pressure is often associated with increasing cloudiness and the possibility of precipitation, whereas rising air pressure generally indicates clearing conditions.

Electronic barometers rather than aneroid barometers are used at locations where pressure is measured and recorded continuously, such as at airports or NWS offices. Electronic barometers convert an electrical signal into a digital pressure value that can be easily transmitted and stored.

Displaying Atmospheric Pressure on Surface and Upper-Air Maps

To make weather forecasts, the National Weather Service produces weather maps and charts that provide symbolic representations of atmospheric conditions at specific points in time. Weather maps show barometric pressure among the other important weather data. In this section we will look at how pressure data and the resulting wind patterns are displayed on weather maps.

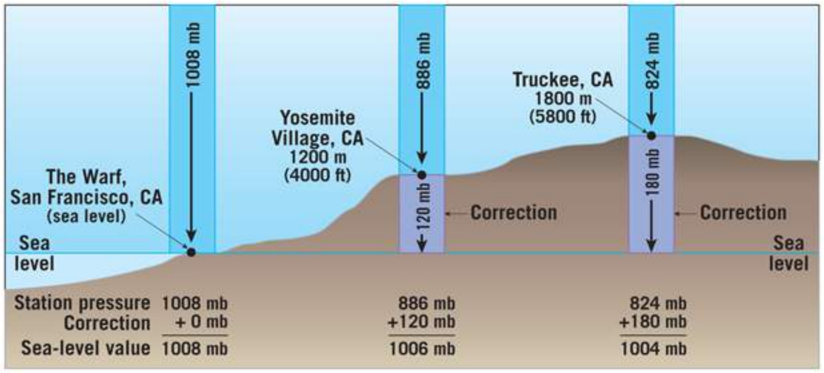
Pressure Readings on Surface Maps

To show pressure patterns over Earth's surface, meteorologists first collect barometric pressure readings, usually measured in millibars (mb), taken at hundreds of weather stations. These readings, called **station pressures**, have not been adjusted for the decline in air pressure that occurs with increasing elevation. Without these adjustments, all regions located at high elevations would be mapped as having low pressure, and locations below sea level, such as Death Valley, California, would always report high pressure readings.

To compensate for altitude, all pressure measurements are converted to *sea-level equivalents* before they are plotted on a surface map. Fortunately, near the surface, pressure decreases almost linearly—at nearly a steady rate—which makes the adjustment relatively easy. Pressure near Earth's surface drops about 1 millibar for each 10 meters of increased elevation—or about 1 inch of mercury for every 1000 feet. Figure 6.5 shows the adjusted air pressure values (*sea-level pressures*) for three locations in California, using this approximation. Because temperature also affects air density, and hence the weight of an air column, temperature is also considered when altitude corrections are made. Normally the correction for temperature is comparatively small, so it is not included in the calculation shown in Figure 6.5.

Figure 6.5 Correcting pressure readings to sea-level equivalence

This is done by adding the pressure that would be exerted by an imaginary column of air to the station's pressure reading. The higher the recording station's elevation, the greater the correction.

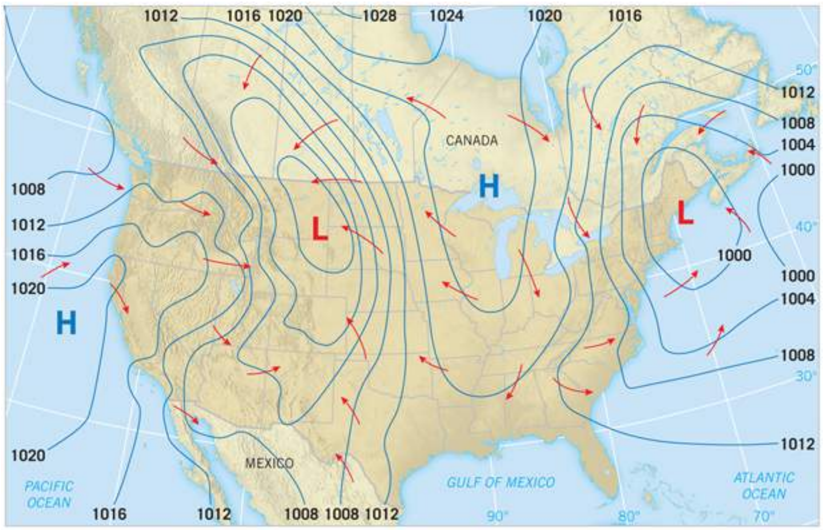


> Station pressures are converted to sea-level pressures to remove the influence of elevation.

Once corrected to sea-level values, the pressure measurements are displayed on surface weather maps using **isobars** (*iso* = equal, *bar* = pressure), lines that connect places of equal air pressure. Figure 6.6 shows a simplified surface weather map. Notice that the isobars are drawn at 4-millibar intervals—that is, at 996, 1000, 1004, and so forth. Closed isobars that roughly resemble circles identify *highs* and *lows*. The pressure in a *high* is greater than that of the surrounding air and is labeled with a large blue *H*, whereas the pressure in a *low* is lower than the surrounding air and is labeled with a large red *L*.

Figure 6.6 Surface weather map

This simplified surface weather map uses isobars of sea-level pressure to show high-pressure systems (anticyclones) and low-pressure systems (cyclones). The idealized wind patterns associated with these pressure systems are shown with red arrows.



In general, *high-pressure systems*, also called **anticyclones**, are associated with dry conditions. *Low-pressure systems* that occur in the middle latitudes are called **cyclones**, or **midlatitude cyclones**, to differentiate them from *tropical cyclones*. (Tropical cyclones are also called *hurricanes* or *typhoons*, depending on their intensity and location.) In contrast to anticyclones, midlatitude cyclones tend to produce stormy weather.

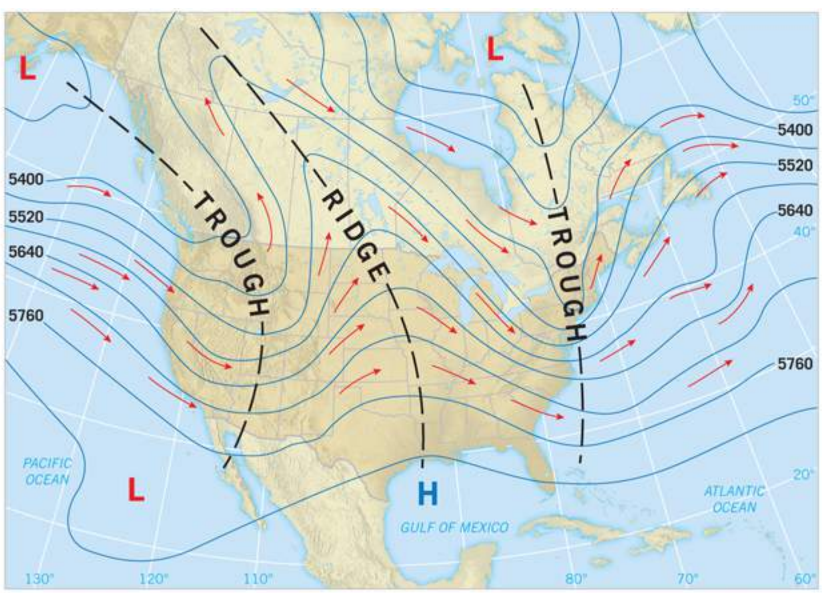
In addition to isobars, the weather maps in Figure 6.6 show the idealized wind patterns with red arrows. Notice that surface winds generally blow at an angle across the isobars, and *away* from areas of higher pressure and *toward* areas of lower pressure.

Upper-Level Weather Charts

In addition to surface maps, the National Weather Service produces weather charts that show atmospheric conditions at 850-, 700-, 500-, 300-, and 200-millibar levels, twice daily. Recall from Chapter 1 that upper-air data come mainly from *radiosondes*, instrument packages carried aloft by weather balloons. Of particular significance is the 500-millibar chart, located at roughly 5600 meters (18,000 feet) in altitude. This is in the middle of the atmosphere in terms of mass—about half of the air is below that level, and half is above (Figure 6.7). The 500-millibar chart is important because major weather systems tend to travel in the direction of the winds at that level.

Figure 6.7 Upper-air weather chart

This upper-air weather chart shows the height contours at the 500-millibar level. Rather than show variations in pressure at fixed heights, upper-level charts are similar to topographic maps in that the contour pattern reveals the "hills" (ridges) and "valleys" (troughs) of a constant-pressure surface. Therefore, *higher-elevation* contours indicate *higher* pressures, and *lower-elevation* contours indicate *lower* pressures. Lines of constant height can be interpreted the same way as isobars.



> Surface winds blow at an angle across the isobars—away from areas of higher pressure and toward areas of lower pressure, whereas upper-level winds blow roughly parallel to the isobars.

Like other upper-air charts, the 500-millibar chart in Figure 6.7 shows variations in the height (in meters) at which 500-millibar level is found. Rather than show variations in pressure at fixed heights, upper-level charts are similar to topographic maps. That is, the contour pattern reveals the "hills" and "valleys" of a constant-pressure surface, in this case the 500-millibar surface. There is a simple relationship between height contours and isobars: places that experience 500-millibar pressure at higher altitudes are subject to higher pressures than places where the height contours indicate lower altitudes. In other words, *higher-elevation* contours indicate *higher* pressures, and *lower-elevation* contours indicate *lower* pressures.

Notice that the contour lines in Figure 6.7 consist mainly of large sweeping curves labeled *ridges* and *troughs*. **Ridges** are elongated high-pressure areas that extend toward the poles and are associated with warm air moving poleward. **Troughs**, by contrast, are elongated areas of low pressure that sweep equatorward and are associated with cool air moving toward the equator.

You might have wondered . . .

Why do my ears sometimes feel painful when I fly?

When airplanes take off and land, some people experience ear pain because of slight changes in cabin pressure. Normally, the air pressure in your middle ear is the same as the pressure of the surrounding atmosphere because the eustachian tube connects the ear to the throat. But the eustachian tubes of a passenger with a cold may become blocked, preventing the flow of air either into or out of the middle ear. When the plane ascends or descends, the resulting pressure change can cause discomfort or, less often, excruciating pain, which subsides when the ears “pop” to equalize the pressure.

Concept Checks 6.1

- What is wind, and what causes the air to move?
- Define *atmospheric pressure* in your own words.
- Describe the atmospheric pressure associated with a cyclone compared to an anticyclone.

6.2 Why Does Air Pressure Vary?

LO 2 Identify the factors affecting air pressure at Earth's surface as well as aloft.

What is the importance of atmospheric pressure and its daily variations? Recall that variations in air pressure cause air to move, which in turn causes changes in temperature and humidity at a given location. In short, differences in air pressure generate local and global winds that bring us our weather. Therefore, the National Weather Service closely monitors changes in air pressure.

Although pressure changes with altitude are important, meteorologists are more interested in the horizontal pressure differences that occur around the globe. Horizontal pressure differences tend to be relatively small, but these small differences are important because they are the main drivers of wind. Extreme readings are rarely more than 30 millibars (1 inch of mercury) above average sea-level pressure or 60 millibars (2 inches) below average sea-level pressure. Occasionally the barometric pressure measured in severe storms, such as hurricanes, is lower (see Figure 6.2). Yet these small differences in air pressure can be sufficient to generate violent winds.

Four primary factors contribute to changes in air pressure: altitude, temperature, humidity, and the movement of a mass of air from one location to another.

Pressure Changes with Altitude

Just as scuba divers experience a decrease in water pressure as they rise toward the surface, we experience a decrease in air pressure as we ascend into the atmosphere. The relationship between air pressure and the air's density largely explains the drop in air pressure that occurs with altitude. Recall that at sea level, a column of air weighs 14.7 pounds per square inch (1013.25 mb) and therefore exerts that amount of pressure. As we ascend through the atmosphere, there is less air above us, and as a result, the air becomes less dense. Therefore, as would be expected, there is a corresponding *decrease in pressure with an increase in altitude*.

Because density decreases with altitude, the term *thin air* is normally associated with mountainous regions. Except for the Sherpas (indigenous peoples of Nepal), most of the climbers who reach the summit of Mount Everest use supplementary oxygen for the final leg of the journey. Even with the extra oxygen, many of these climbers experience periods of disorientation because of an inadequate supply of oxygen to their brains.

You might have wondered . . .

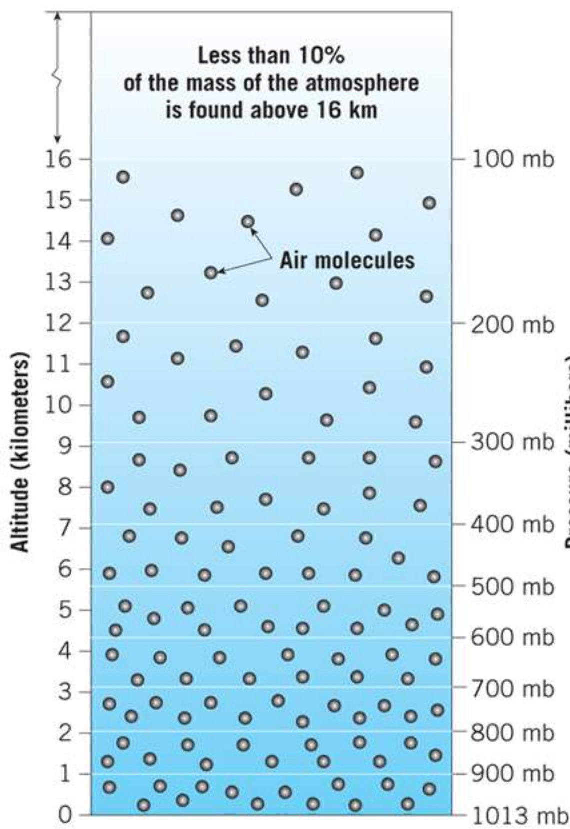
Do spaghetti noodles cook faster at higher elevations?

In a city like San Diego (located near sea level), water boils at about 100°C (212°F). However, in Denver, Colorado—the Mile High City—water boils at about 95°C (203°F) because of lower air pressure. Although water comes to a boil faster in Denver than in San Diego, it takes longer to cook spaghetti noodles in Denver because the noodles cook at a lower temperature.

Recall from Chapter 1 that the rate at which pressure decreases with altitude is not constant. The rate of decrease is much greater near Earth's surface, where pressure is high, than aloft, where air pressure is low. A model of the **U.S. standard atmosphere**, shown in Figure 6.8, depicts the idealized vertical distribution of atmospheric pressure at various altitudes.

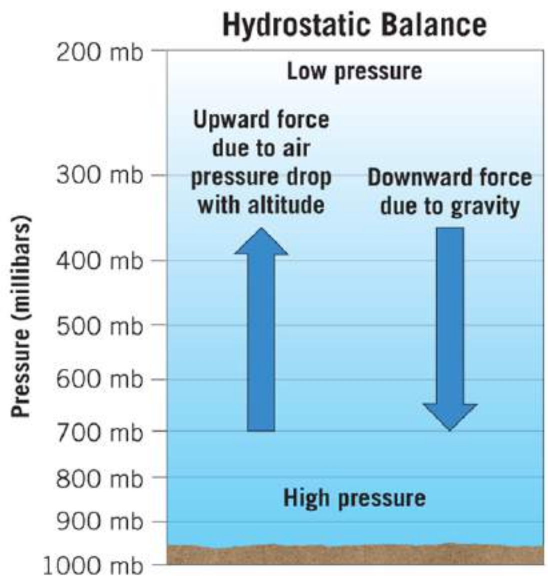
Figure 6.8 **Illustration of the U.S. standard atmosphere**

Each layer contains about 10 percent of the atmosphere. Notice that at roughly 5.6 kilometers (18,000 feet), the pressure is about one-half of its sea-level value.



Because pressure decreases with height, there is always higher pressure near the surface and lower pressure aloft. Because air moves from high-pressure areas to low-pressure areas, you might reason that air near the surface would flow upward toward outer space. However, gravity prevents this from occurring by balancing the upward force so that air is concentrated near the Earth's surface. The balance between the upward push of air toward space and the downward force of gravity is called **hydrostatic balance** (Figure 6.9).

Figure 6.9 Hydrostatic balance in the atmosphere



Hydrostatic balance is the balance between the upward push of air toward space and the downward pull of gravity.

Pressure Changes with Temperature

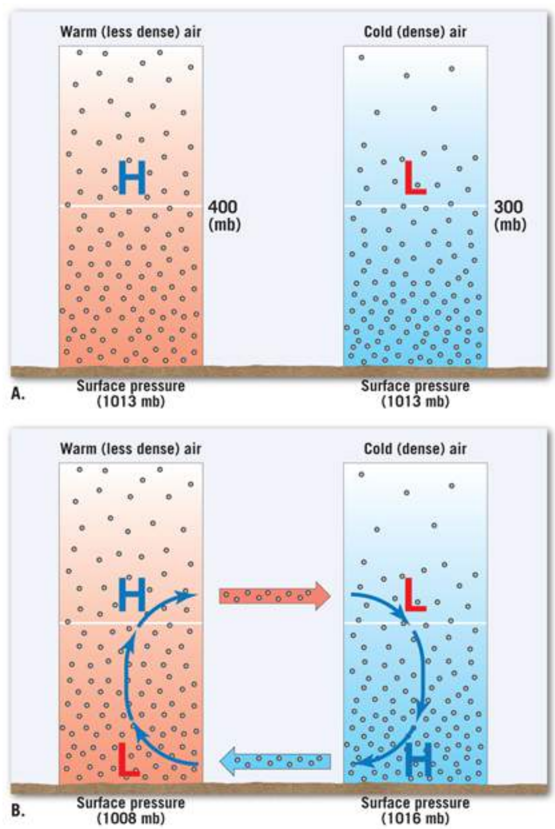
How do horizontal pressure differences arise? Picture northern Canada in midwinter. Here the snow-covered surface is continually radiating heat to space while receiving minimal incoming solar radiation. The frigid ground cools the air above, such that daily lows of –34°C (–30°F) are common. Just the opposite conditions occur over the American Southwest in July and August, when temperatures regularly exceed 40°C (104°F).

A Cold Air Column Versus a Warm Air Column

Recall that temperature is a measure of average molecular motion (kinetic energy). Thus, the cold Canadian air described above is composed of slow-moving molecules that are packed closely together. By contrast, warm air is composed of faster-moving air molecules spaced farther apart. This concept is illustrated in Figure 6.10A, which shows two hypothetical columns of air with identical masses (same number of air molecules) that exert the same surface pressure. The spacing of air molecules represents differences in density. Because of these differences, air pressure drops more rapidly with altitude in a column of cold (dense) air than in a column of warm (less dense) air. (This phenomenon has implications in aviation, as described in Box 6.1.)

Figure 6.10 **A comparison of the densities of a column of cold air and a column of warm air**

A. Air pressure decreases more rapidly with altitude in a cold air column because the molecules are closely packed (denser). Looking at the line drawn halfway up the two columns, notice that there are more air molecules above this line in the warm air column than there are in the cold column. **B.** As air aloft leaves the warm air column, the mass of air in that column decreases. This mass transfer of air from the warm column to the cold column results in a higher surface pressure in the cold air column. Higher surface pressure in the cold air column in turn generates a surface flow (wind) toward the warm air column.



Box 6.1

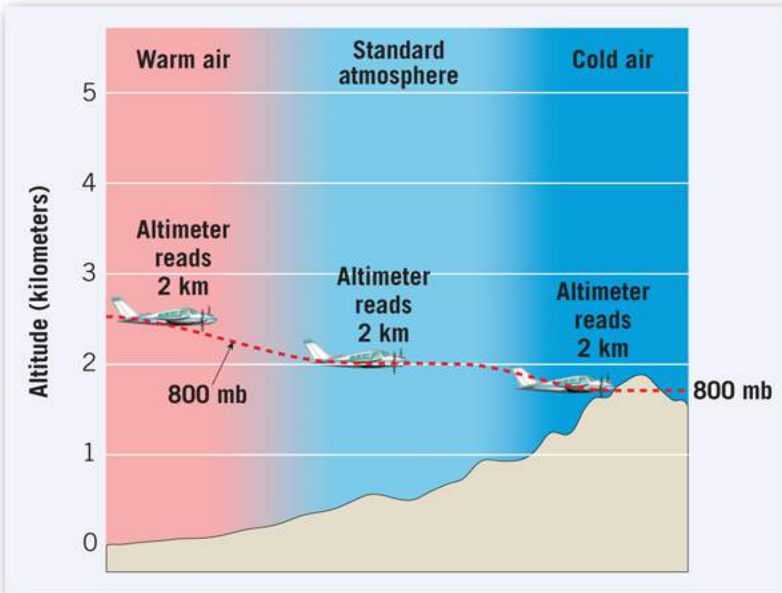
Air Pressure and Aviation

The cockpit of nearly every aircraft contains a *pressure altimeter*, an instrument that allows a pilot to determine the plane's altitude. A pressure altimeter is essentially an aneroid barometer marked in meters instead of millibars and, as such, responds to changes in air pressure. For example, Figure 6.8 shows that the standard atmospheric pressure of about 800 millibars "normally" occurs at a height of 2 kilometers. Therefore, when the pressure reaches 800 millibars, the altimeter will indicate an altitude of 2 kilometers.

Because of temperature variations and moving pressure systems, actual conditions usually differ from that shown by an aircraft's altimeter. When the air is warmer than predicted by the standard atmosphere, the plane will fly higher than the height indicated by the altimeter. By contrast, in cold air, the plane will fly lower than indicated. This could be especially dangerous if the pilot is flying a small plane through mountainous terrain with poor visibility (Figure 6.A). To avoid dangerous situations, pilots make altimeter corrections before takeoffs and landings, and they sometimes make corrections en route as well.

Figure 6.A Aircraft altimeters

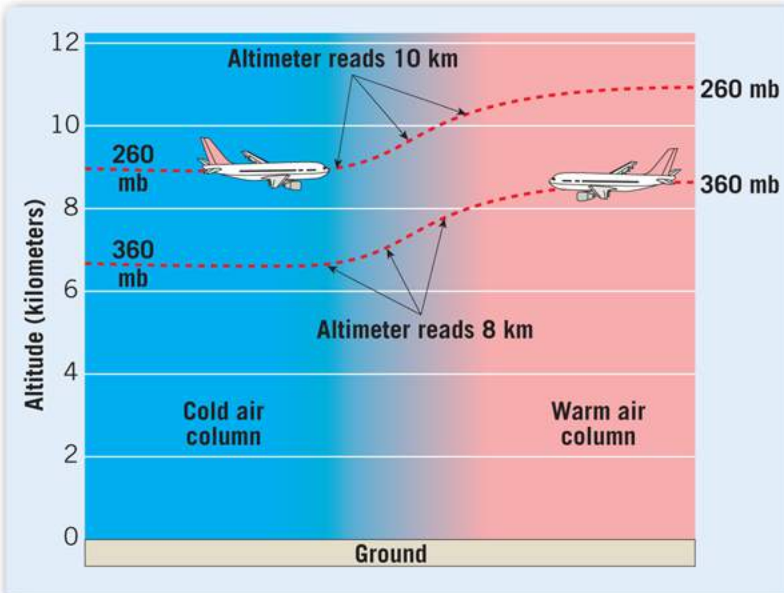
When a plane flies into a cold air mass, its altitude is lower than shown on the altimeter, which can be a problem in mountainous terrains.



Above about 5.6 kilometers (18,000 feet), pressure changes are more gradual, so corrections cannot be made as precisely as at lower levels. Consequently, commercial aircraft have their altimeters set at the standard atmosphere and fly paths of constant pressure, called *flight levels*, instead of constant altitude (Figure 6.B). In other words, when an aircraft flies at a constant altimeter setting, a temperature variation will result in a change in the plane's altitude. When the temperature increases (warm air column) along a flight path, the plane will climb, and when the temperature decreases (cold air column), the plane will descend. There is little risk of midair collisions because nearby aircraft are assigned different flight levels in order to maintain sufficient separation.

Figure 6.B **Flying a path of constant pressure**

Commercial aircraft above 5.6 kilometers (18,000 feet) generally fly paths of constant pressure instead of constant altitude.



Large commercial aircraft also use radar altimeters to measure heights above the terrain. The time required for a radio signal to reach the surface and return is used to accurately determine the height of the plane above the ground. This system is not without drawbacks; a radar altimeter provides the elevation above the ground rather than above sea level, so knowledge of the underlying terrain is required. However, radar altimeters are useful for measuring the height above ground level during landing.

Apply What You Know

1. Compare and contrast a pressure altimeter and an aneroid barometer.
2. When are radar altimeters used?

Notice the line drawn halfway up the two columns in Figure 6.10A. In the cold air column, there are fewer air molecules above this altitude as compared to the warm column. Hence, the air pressure aloft must be less (labeled L for *low* pressure) in the cold column than in the warm column—labeled H for *high* pressure. We can conclude, therefore, that the difference in air temperatures between these two air columns creates a horizontal difference in air pressure aloft.

> Air pressure drops more rapidly with altitude in a column of cold (dense) air than in a column of warm (less dense) air, which creates a horizontal difference in air pressure aloft.

How Do Horizontal Pressure Differences Generate Wind?

Let's assume that the molecules in the two hypothetical columns of air in Figure 6.10B are permitted to flow horizontally at the altitude above the white line. The air molecules would move from the area higher pressure (warm air column) toward the area of lower pressure (cold air column). The force that causes air to move from higher pressure toward lower pressure is called the *pressure gradient force* and will be discussed in Section 6.3.

As air aloft leaves the warm air column, the mass of air in that column decreases, causing a decrease in the surface pressure (lower pressure)—shown by the L near the ground. At the same time, the mass of air transferred from the warm column to the cold column results in a higher surface pressure in the cold air column. This higher surface pressure in the cold column in turn generates a surface flow from the cold column to the warm column. Simultaneously, the loss of surface air from the cold column causes the air in that column to sink, while the loss of air aloft in the warm column causes the air to rise. These vertical motions complete the circulation pattern shown in Figure 6.10B.

Relationship Between Air Pressure and Temperature

An important relationship exists between air pressure and temperature, as you saw in the preceding discussion. Temperature variations create pressure differences and, ultimately, wind. Daily temperature differences caused by unequal heating of different land surfaces tend to be confined to a zone only a few kilometers thick, which produce local winds. On a global scale, however, variations in the amount of solar radiation received in the polar versus the equatorial latitudes generate much larger pressure systems that, in turn, produce the planetary atmospheric circulation.

> The main cause of pressure differences and, as a result, wind is *unequal heating of Earth's surface*.

Pressure Changes with Moisture Content

Although less important than temperature, the amount of water vapor contained in a volume of air influences its density. Contrary to popular perception, water vapor *reduces* the density of air. The air may feel "heavy" on hot, humid days, but it is not. You can easily verify this fact for yourself by examining a periodic table of the elements and noting that the molecular weights of nitrogen (N_2) and oxygen (O_2) are greater than that of water vapor (H_2O). (These gases have relative mass of 28, 38, and 18 grams, respectively.) Another way to think about this is to remember that water does not evaporate readily when the humidity is high, so on a humid day the sweat on your skin will not evaporate very quickly. This leads to the "heavy" feeling.

In a volume of air, the molecules of these gases are intermixed, and each takes up roughly the same amount of space. As the water content of an air mass increases, lighter water vapor molecules displace heavier nitrogen and oxygen molecules. Therefore, humid air is lighter (less dense) than dry air. The effect on pressure is similar to that of a warm air column, though much smaller. Even very humid air is only about 2 percent less dense than dry air at the same temperature.

Pressure Changes Caused by Airflow

As you saw in Figure 6.10, when the warm and cold columns of air interact, the movement of air causes changes in air pressure at the surface. For example, in situations where there is a net flow of air into a region, air accumulates. This phenomenon, called **convergence**, causes air to be squeezed into a smaller space, which results in an air column exerting more force on the surface, increasing air pressure. By contrast, in regions where there is a net outflow of air, a situation referred to as **divergence**, the surface pressure drops. We will return to the important mechanisms of convergence and divergence, which generate areas of high and low pressure, later in this chapter.

> A net flow of air into a region is called *convergence* and a net outflow of air is called *divergence*.

Concept Checks 6.2

- Describe how winds blow in relation to areas of high pressure and low pressure.
- Explain why a cold, dry air mass produces a higher surface pressure than a warm, humid air mass in the absence of weather systems.
- Explain how horizontal convergence and divergence affect surface pressure.

6.3 Factors Affecting Wind

LO 3 List and describe the three forces that act on the atmosphere to either create or alter winds.

If Earth did not rotate and if there were no friction, air would flow directly from areas of higher pressure to areas of lower pressure. However, because both factors exist, wind is controlled by a combination of forces, including:

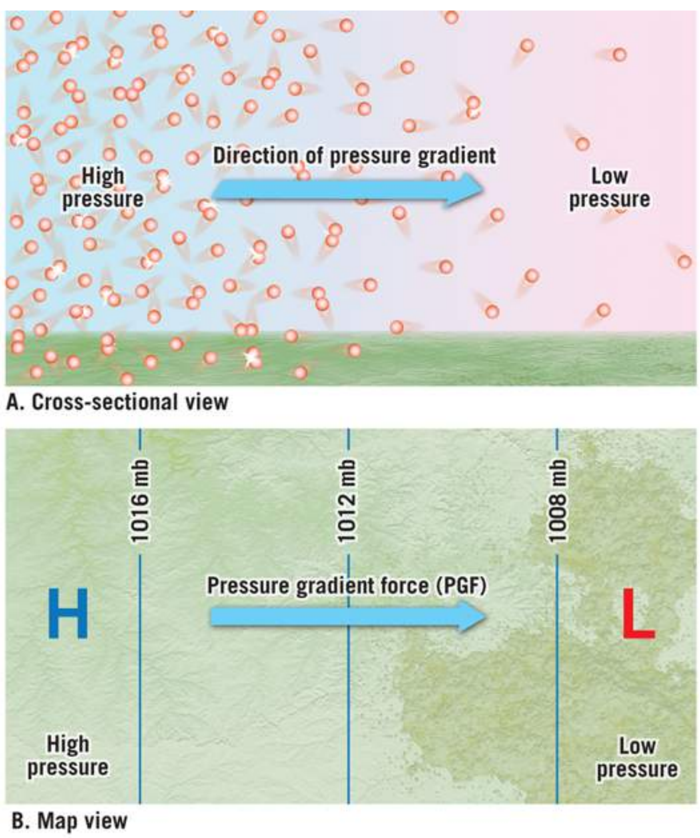
1. Pressure gradient force
2. Coriolis force
3. Friction

Pressure Gradient Force

If an object experiences an unbalanced force in one direction, it will accelerate (experience a change in velocity). The force that generates winds results from horizontal pressure differences. When air is subjected to greater pressure on one side than on another, the imbalance produces a force, called the **pressure gradient force (PGF)**, which is directed from areas of higher pressure toward areas of lower pressure Figure 6.11. Thus, pressure differences cause the wind to blow, and the greater these differences, the greater the wind speed.

Figure 6.11 Pressure gradient force (PGF)

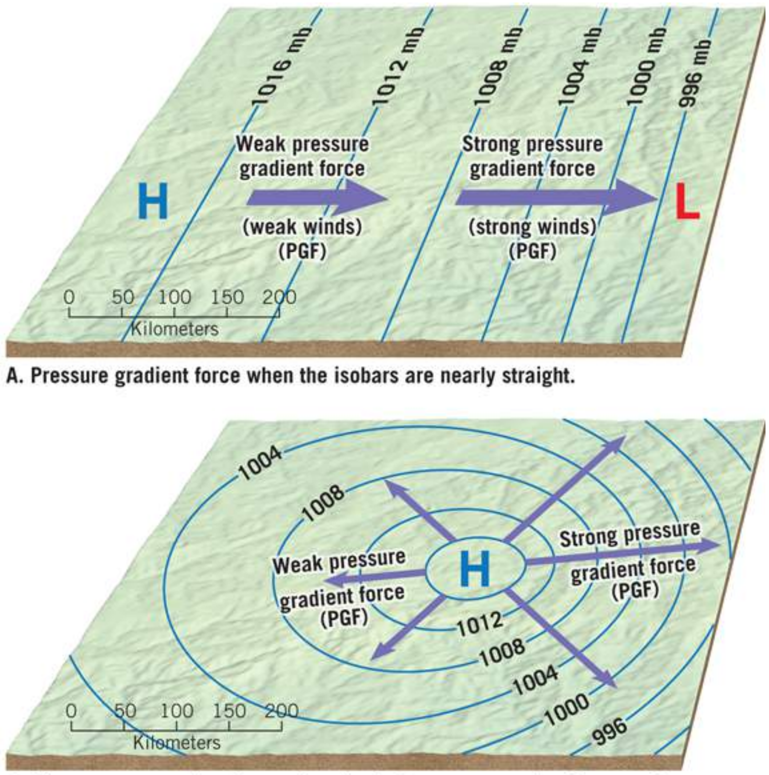
A. Air moves from areas of high pressure toward areas of low pressure. **B.** The pressure gradient force is directed perpendicular to the isobars.



Recall that isobars are used on surface maps to show horizontal pressure patterns. The *spacing* of the isobars indicates the amount of pressure change occurring over a given distance, called the **pressure gradient**. The pressure gradient is analogous to gravity acting on a ball rolling down a hill. A steep (or *strong*) pressure gradient, like a steep hill, causes greater acceleration of a parcel of air than does a weak pressure gradient (a gentle hill). Thus, the relationship between wind speed and the pressure gradient is straightforward: *Closely spaced isobars indicate a steep pressure gradient and strong winds; widely spaced isobars indicate a weak pressure gradient and light winds.* Figure 6.12A illustrates the relationship between the spacing of isobars and the pressure gradient force. Note also that the pressure gradient force is always directed at *right angles* to the isobars. When the isobars are curved, the pressure gradient force radiates out from the area of higher pressure and toward areas of lower pressure, as illustrated in Figure 6.12B.

Figure 6.12 **Isobars are lines connecting places of equal atmospheric pressure**

The spacing of isobars indicates the amount of pressure change occurring over a given distance. Closely spaced isobars indicate a strong pressure gradient and high wind speeds, whereas widely spaced isobars indicate a weak pressure gradient and low wind speeds.



A. Pressure gradient force when the isobars are nearly straight.

B. The pressure gradient force when the isobars are curved or form nearly concentric circles.

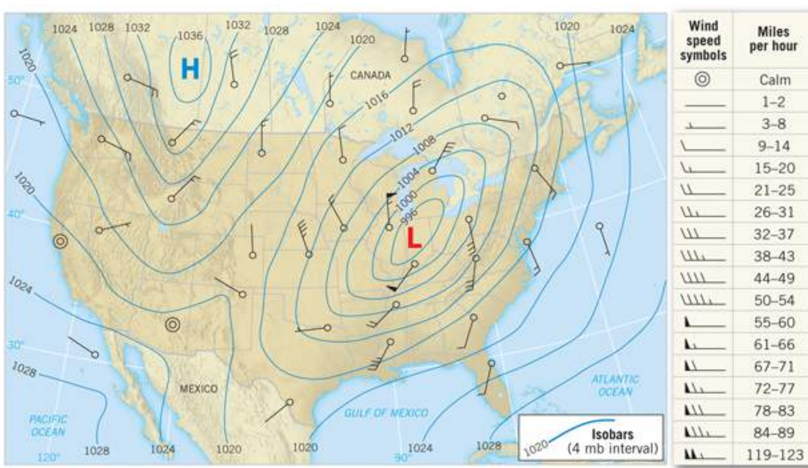
The pressure gradient force (PGF) is directed perpendicular to isobars and from higher pressure toward lower pressure. More closely spaced isobars indicate a stronger PGF and faster wind speeds.

Coriolis Force

The weather map in Figure 6.13 shows the typical airflow associated with surface high- and low-pressure systems. As expected, the air moves out of the regions of higher pressure and into the regions of lower pressure. However, the wind does not cross the isobars at right angles, as the pressure gradient force directs. This deviation is a result of Earth's rotation and has been named the **Coriolis force**, after the French scientist Gaspard-Gustave Coriolis, who first expressed its magnitude quantitatively. It is important to note that the Coriolis force does not generate wind; rather, *it modifies the direction of airflow*.

Figure 6.13 **Isobars show the distribution of sea-level pressures on surface weather maps**

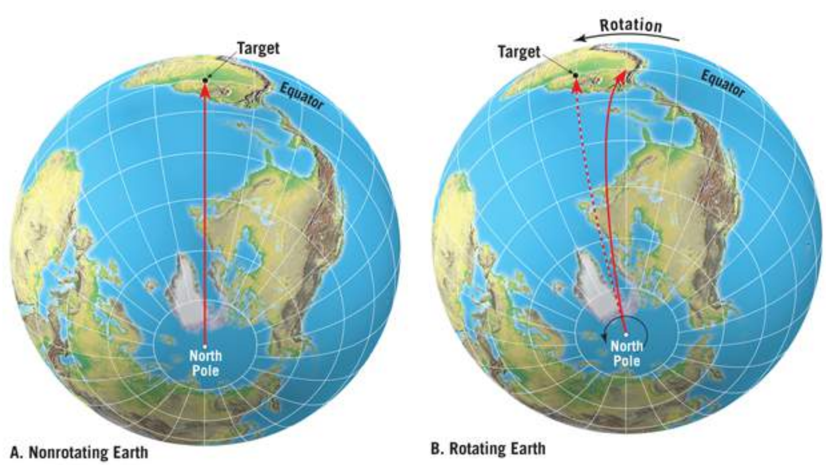
Isobars are seldom straight but usually form broad curves. Concentric isobars indicate cells of high and low pressure. The "wind flags" indicate the expected airflow surrounding pressure cells and are plotted as "flying" with the wind (that is, the wind blows toward the station circle). Notice on this map that the isobars are more closely spaced and the wind speed is faster around the low-pressure center than around the high.



The Coriolis force causes all free-moving objects, including wind, to be deflected to the *right* of their path of motion in the Northern Hemisphere and to the *left* in the Southern Hemisphere. The reason for this deflection can be illustrated by imagining the path of a rocket launched from the North Pole toward a target on the equator (Figure 6.14). If the rocket travels 1 hour toward its target, Earth would have rotated 15° to the east during its flight. To someone watching the rocket's path from the location of the intended target, it would look as if the rocket veered off its path and hit Earth 15° west of its target (Figure 6.14B). The true path of the rocket was straight and would appear as such to someone in space looking toward Earth. Earth's rotation under the rocket produced the *apparent* deflection.

Smartfigure 6.14 **The Coriolis force**

The effects of the Coriolis force illustrated by a rocket traveling for 1 hour from the North Pole to a location on the equator. **A.** On a nonrotating Earth, the rocket would fly straight to its target. **B.** However, Earth rotates 15° each hour. Thus, although the rocket travels in a straight line, when we plot the path of the rocket on Earth's surface, it follows a curved path that veers to the right of the target.



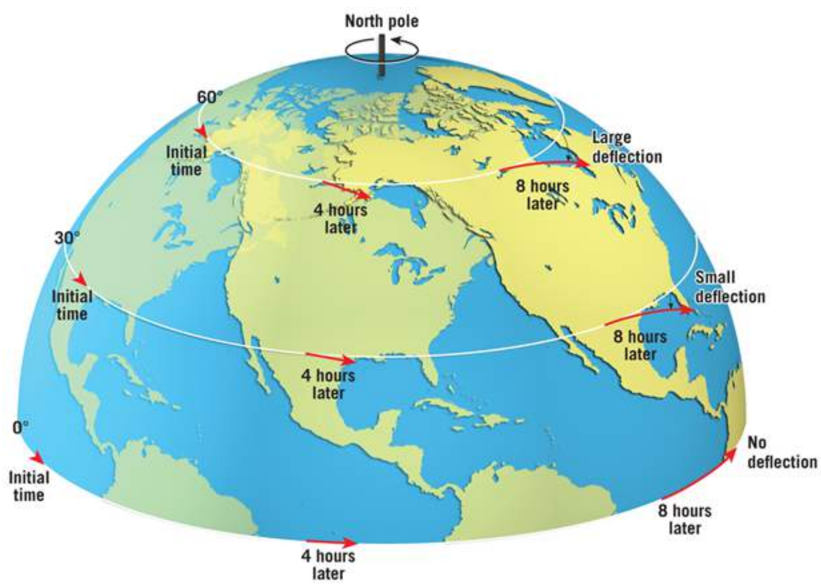
Watch **SmartFigure: The Coriolis Effect**

Watch **Video: The Coriolis Effect on a Merry-Go-Round**

It is usually easy to visualize Coriolis deflection when the motion is from north to south, as in our rocket example, but it is not as easy to see how a west-to-east flow would be deflected. Figure 6.15 illustrates this situation, using winds blowing eastward at three different latitudes (0°, 30°, and 60°). Notice that after a few hours, the winds along the 30th and 60th parallels appear to be veering off course. However, when viewed from space, it is apparent that these winds have maintained their original direction. It is the “change” of orientation of North America as Earth rotates on its axis that produces the deflection we observe in Figure 6.15.

Figure 6.15 **Coriolis deflection of winds blowing eastward at different latitudes**

After a few hours, the winds along the 30th and 60th parallels appear to veer off course. This deflection (which does not occur at the equator) is caused by Earth's rotation, which changes the orientation of the surface over which the winds are moving.

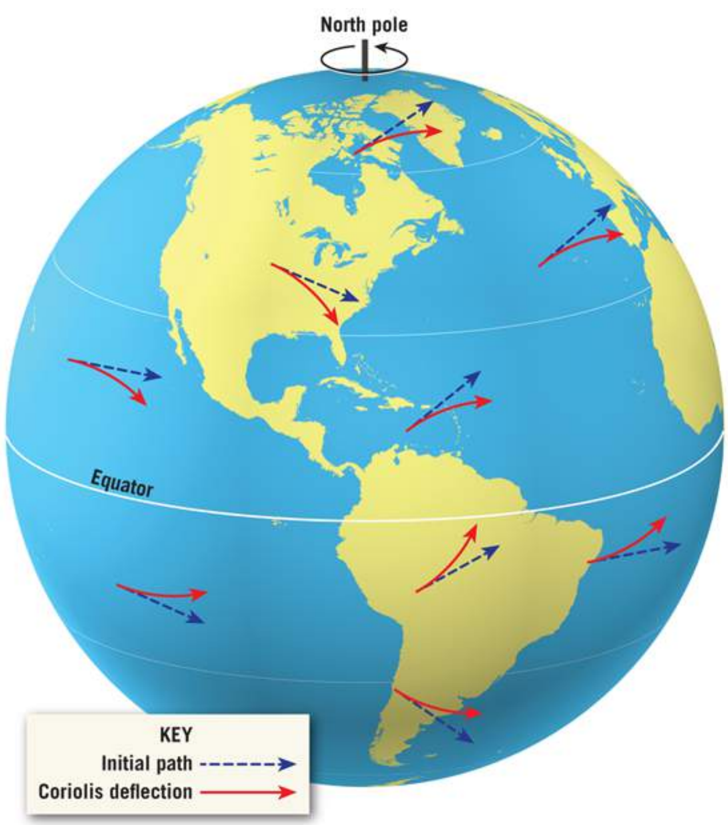


We can also see in Figure 6.15 that the amount of deflection is greater at 60° latitude than at 30° latitude. Furthermore, there is no deflection observed for the airflow along the equator. We conclude, therefore, that the magnitude of the Coriolis force is dependent on latitude; it is strongest at the poles and weakens equatorward, where it eventually becomes nonexistent. Also note that the amount of Coriolis deflection increases with wind speed because faster winds travel farther than slower winds in the same time period.

Because of the *counterclockwise* rotation of Earth as viewed from above the North Pole, the winds in the Northern Hemisphere are deflected to the right of their initial path of motion (Figure 6.16). In the Southern Hemisphere, however, Earth exhibits a *clockwise* rotation. (To visualize this, look down on a globe that has a counterclockwise rotation and then look at it from below—a Southern Hemisphere point of view.) As a result, the Coriolis force produces a similar deflection in the Southern Hemisphere, but to the left of the initial path of motion (Figure 6.16).

Figure 6.16 Coriolis deflection of winds in both hemispheres

The Coriolis force causes winds in the Northern Hemisphere to be deflected to the right of their initial path of motion, whereas in the Southern Hemisphere they are deflected to the left of their initial path.



All "free-moving" objects are affected by the Coriolis force, including airplanes, artillery, and rockets. This fact was dramatically discovered by the U.S. Navy at the beginning of World War II. During target practice, long-range guns on battleships continually missed their targets by as much as several hundred yards until ballistic corrections were made for the changing position of seemingly stationary targets. Across short distances, however, the Coriolis force is relatively small. Nevertheless, in the middle latitudes, this deflecting force is great enough to potentially affect the outcome of a baseball game. A ball hit a horizontal distance of 100 meters (330 feet) in 4 seconds down the right field line will be deflected 1.5 centimeters (more than 0.5 inch) to the right by the Coriolis force—enough to turn a potential home run into a foul ball!

> The Coriolis force is directed perpendicular to the wind—to the right of the direction of airflow in the Northern Hemisphere and to the left in the Southern Hemisphere.

In summary, the Coriolis force acts to change the direction of a moving body to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. This deflecting force (1) is always directed at right angles to the direction of airflow; (2) affects only wind direction, not speed; (3) is proportional to wind speed, so that the stronger the wind, the greater the deflecting force; and (4) is strongest at the poles and weakens equatorward, becoming nonexistent at the equator.

Friction

Recall that the pressure gradient force is the primary driving force of wind. As an unbalanced force, it causes air to accelerate from regions of higher pressure toward regions of lower pressure. **Friction**, by contrast, acts to slow moving objects and decrease wind speeds—mainly surface winds. The force of friction is greater for faster winds and zero in calm conditions. In addition, the effect of friction depends on the surface over which the wind is blowing. Very rough terrain has a larger friction force than flat, barren land surfaces or the ocean, which is comparatively smooth.

By slowing airflow, friction also reduces the Coriolis force. Thus, not only is airflow near the surface slower than winds aloft, but the direction of flow is also altered. As we will see in the next section, winds aloft flow nearly parallel to the isobars, whereas wind near the surface flows across the isobars at an angle, depending on the region's topography.

You might have wondered . . .

Do baseballs really fly farther at Denver's Coors Field?

Coors Field has become known as the "homerun hitter's ballpark" because it led all Major League ballparks in total home runs during its first decade. In theory, a well-struck baseball should travel roughly 10 percent farther in Denver (elevation 5280 feet) because of lower air density (and therefore less friction) than it would in a ballpark at sea level. However, a group of researchers concluded that the assumed elevation enhancement of fly ball distance has been greatly overestimated; these researchers found that other weather conditions, mainly the prevailing winds around the ballpark (blowing predominantly from home plate toward the outfield), aid the hitters.

Friction significantly influences airflow only in the first 1.5 kilometers (1 mile) of Earth's atmosphere, often referred to as the **boundary layer**. The effect of friction is negligible above that height. As a result, upper-level flow is less complicated than surface winds. We analyze both types of flow in the next section.

> Friction, which is greatest near Earth's surface, slows surface winds.

Concept Checks 6.3

■ List and describe three forces that combine to direct wind (horizontal airflow).

■ Write a generalization relating the spacing of isobars to wind speed.

■ Briefly describe how the Coriolis force and friction modify air movement.

6.4 Winds Aloft Versus Surface Winds

LO 4   Explain why winds aloft flow roughly parallel to the isobars, whereas surface winds travel at an angle across the isobars.

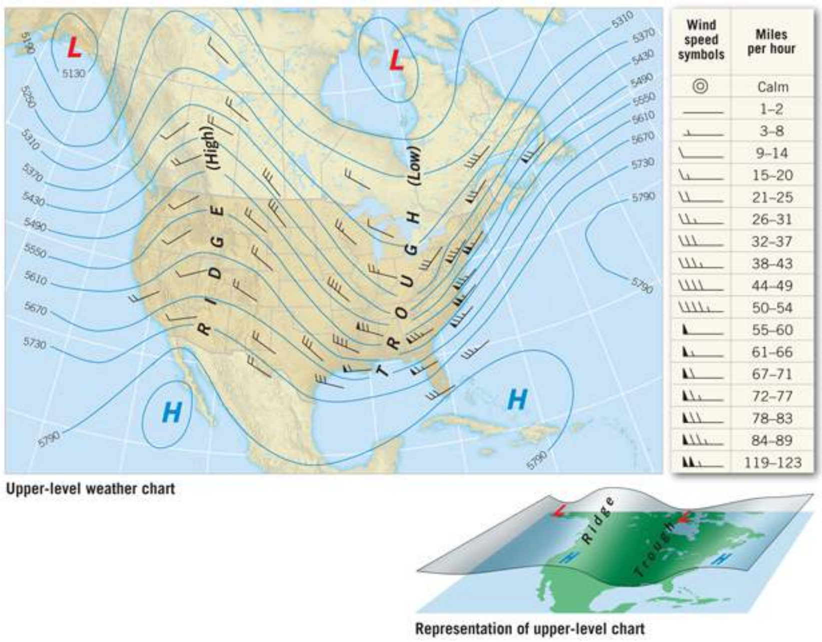
In this section we address airflow aloft—at least 1.5 kilometers above Earth's surface, where the force of friction is not significant enough to affect the flow of winds. We then analyze winds at the surface, where friction significantly influences airflow.

Straight-line Flow and Geostrophic Winds

As shown in Figure 6.17, the winds aloft tend to flow parallel to the lines of constant height. These *isolines* can be interpreted the same way as isobars. In regions where the isobars are relatively straight and evenly spaced, the resulting winds flow in roughly straight lines, parallel to the isobars. This phenomenon, called **geostrophic wind**, is generated when a balance is reached between the Coriolis force and the pressure gradient force.

Figure 6.17 Simplified upper-air weather chart

This weather chart shows the direction and speed of the upper-air winds. Note from the wind flags that the airflow is almost parallel to the contours. Like most other upper-air charts, this one shows variations in the height (in meters) at which a selected pressure (500 millibars) is found instead of showing variations in pressure at a fixed height, like surface maps. Places experiencing 500-millibar pressure at higher altitudes (toward the south on this map) are experiencing higher pressures than places where the height contours indicate lower altitudes. Thus, *higher-elevation* contours indicate *higher* pressures, and *lower-elevation* contours indicate *lower* pressures.



Upper-level weather chart

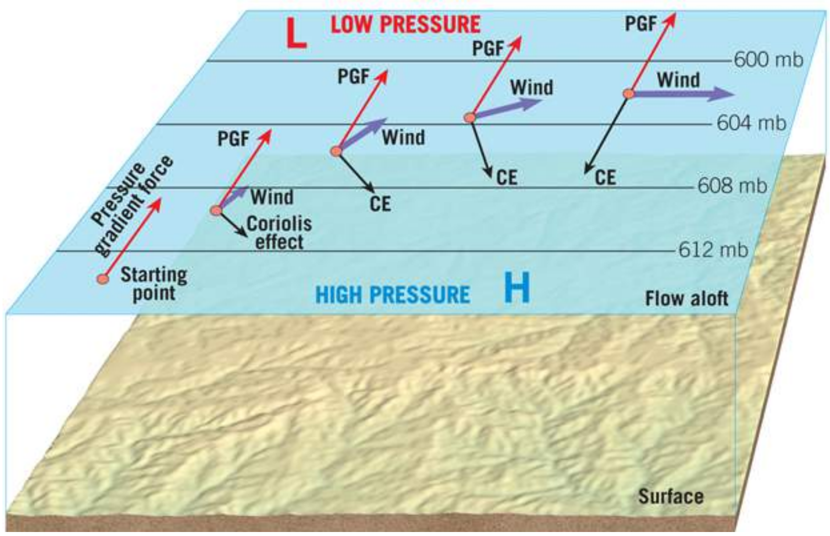
Wind speed symbols	Miles per hour
◎	Calm
	1–2
	3–8
	9–14
	15–20
	21–25
	26–31
	32–37
	38–43
	44–49
	50–54
	55–60
	61–66
	67–71
	72–77
	78–83
	84–89
	119–123

Figure 6.18 illustrates the formation of geostrophic winds. We begin with a nonmoving parcel of air directed by the pressure gradient force (PGF) from an area of high pressure near the bottom of the diagram to the low-pressure area at the top. Initially our parcel of air has no motion, and the Coriolis force (CF) is nonexistent. Under the influence of the pressure gradient force, the parcel begins to accelerate from the area of high pressure toward the area of low pressure. As soon as the parcel begins to move, the Coriolis force commences and causes a deflection to the right for winds in the Northern Hemisphere. As the parcel accelerates,

the strength of the Coriolis force increases because the magnitude of the Coriolis force is proportional to wind speed: The greater the wind speed, the greater the deflection.

Figure 6.18 **Geostrophic wind**

As a parcel of air is accelerated by the pressure gradient force (PGF), the Coriolis force (CF) deflects the wind to the right in the Northern Hemisphere. Eventually the PGF and CF are in balance (equal, but opposite directions), and the wind blows with a constant speed parallel to the isobars. This is called a *geostrophic wind*. It is important to note that in the "real" atmosphere, isobars are rarely straight and parallel, so airflow continually adjusts for variations in the pressure field.



Geostrophic winds, which flow roughly parallel to straight isobars, are created by a balance between the pressure gradient force and the Coriolis force.

Eventually, the wind turns so that it is flowing parallel to the isobars, at which point the pressure gradient force is exactly balanced by the opposing Coriolis force (Figure 6.18). As long as these forces remain balanced, the resulting wind continues to flow at a constant speed parallel to the isobars. Stated another way, the wind is coasting (not accelerating or decelerating) along a pathway defined by the isobars. Under these idealized conditions, when the Coriolis force is exactly equal to the pressure gradient force but acting in the opposite direction, the airflow is said to be in *geostrophic balance*.

Geostrophic winds flow in relatively straight paths, parallel to the isobars, with velocities proportional to the pressure gradient force (see Figure 6.17). A strong pressure gradient (contour lines closer together) creates strong winds, and a weak pressure gradient (contour lines farther apart) produces light winds.

It is important to note that the geostrophic wind is an idealized model that only approximates the actual behavior of airflow aloft. Under normal conditions, the isobars are rarely straight and uniformly spaced, so winds are never purely geostrophic. Nonetheless, the geostrophic model offers a useful estimation of the actual winds aloft. By measuring and mapping the pressure field (orientation and spacing of isobars) that exists aloft, meteorologists can determine both wind direction and speed (see Figure 6.17).

Winds above a few kilometers can be considered geostrophic—that is, flowing parallel to the isobars at speeds that can be calculated from the pressure gradient. A major departure from geostrophic flow are winds that travel along curved paths, like those associated with high- and low-pressure systems and hurricanes.

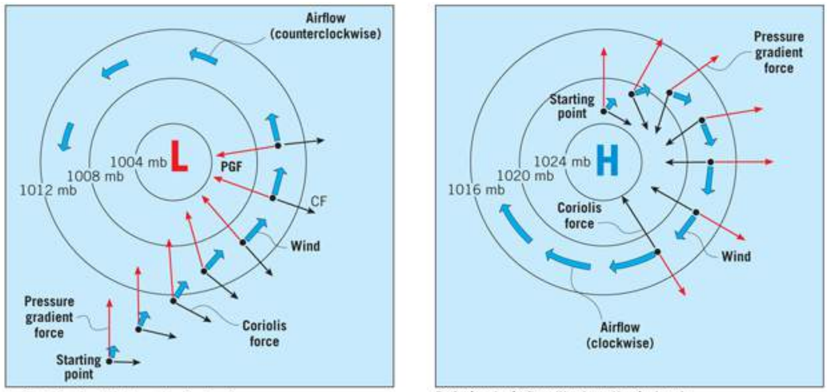
Curved Flow and Gradient Winds

A glance at the upper-level weather chart in Figure 6.17 shows that the isobars (contours) are not generally straight; instead, they make broad, sweeping curves. Occasionally these contour lines connect to form roughly circular cells of either high or low pressure. Thus, unlike geostrophic winds that flow along relatively straight paths, winds around cells of high or low pressure follow highly curved paths. Winds of this nature, which blow roughly parallel to curved isobars, are called **gradient winds**.

Let us examine how the pressure gradient force and Coriolis force combine to produce gradient winds. Figure 6.19A shows the gradient flow around a center of low pressure. As soon as the flow begins, the Coriolis force causes the air to be deflected. In the Northern Hemisphere, where the Coriolis force deflects the flow to the right, the resulting wind blows counterclockwise about a low. Conversely, around a high-pressure cell, the outward-directed pressure gradient force is opposed by the inward-directed Coriolis force, and a clockwise flow results. Figure 6.19B illustrates this idea. (Because the Coriolis force deflects the winds to the left in the Southern Hemisphere, the flow is reversed—clockwise around low-pressure centers and counterclockwise around high-pressure centers.)

Figure 6.19 **Gradient wind**

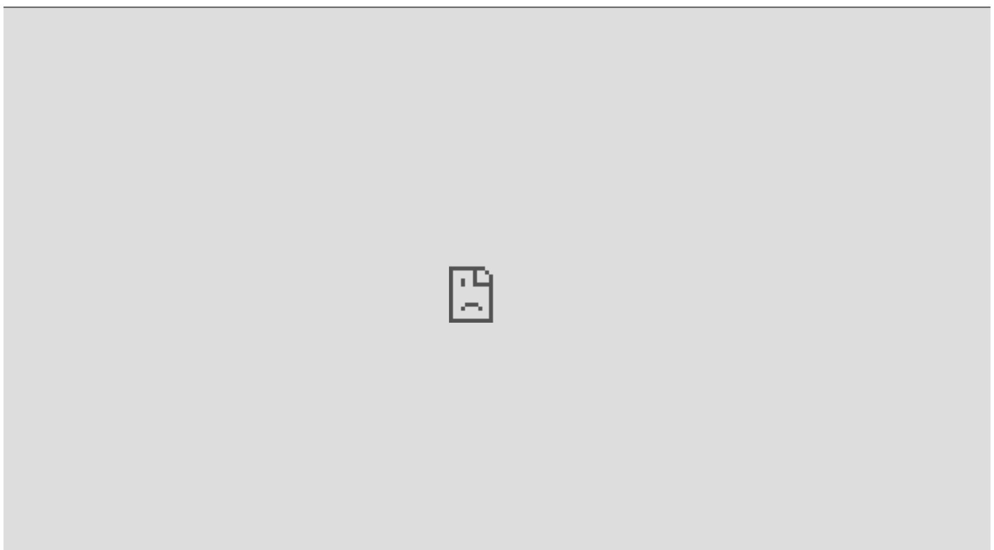
A. Idealized airflow aloft around a low-pressure center (cyclone). **B.** Idealized airflow aloft around a high-pressure center (anticyclone).



A. Cyclonic flow (Northern Hemisphere)

B. Anticyclonic flow (Northern Hemisphere)

Watch **Animation: Wind Pattern Development**



> Winds that blow roughly parallel to curved isobars are called gradient winds.

Meteorologists call centers of low pressure *cyclones* and the flow around them *cyclonic*. There are several types and scales of cyclones. Large low-pressure systems that are major weather makers in the United States are called *midlatitude cyclones*. Other examples include *tropical cyclones* (hurricanes), which are generally smaller than midlatitude cyclones, and *tornadoes*, which are tiny and extremely intense cyclonic storms. **Cyclonic flow** has the same direction of rotation as Earth: counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere. Centers of high pressure are called *anticyclones* and exhibit **anticyclonic flow** (opposite that of Earth's rotation).

Recall that whenever isobars curve to form elongated regions of low and high pressure aloft, these areas are called *troughs* and *ridges*, respectively (see Figure 6.17). The flow around a trough is cyclonic; conversely, the flow around a ridge is anticyclonic.

Now let us consider the forces that produce the gradient flow associated with cyclonic and anticyclonic circulations. Wherever the flow is curved, a force has deflected the air (changed its direction), even when no change in speed results. This is a consequence of Newton's first law of motion, which states that a moving object will continue to move in a straight line* unless acted upon by an unbalanced force. You have undoubtedly experienced the effect of Newton's law when the automobile in which you were riding turned sharply and your body tried to continue moving straight ahead (see Appendix E).

Figure 6.19A shows us that in a low-pressure center, the inward-directed pressure gradient force is opposed by the outward-directed Coriolis force. But to keep the path curved (parallel to the isobars), the inward pull of the pressure gradient force must be strong enough to balance the Coriolis force as well as to turn (accelerate) the air inward. The inward turning of the air is called *centripetal acceleration*. As a result, in a low-pressure system, the Coriolis force must be weaker than the pressure gradient force to create the balance required to allow air to flow around a curved trajectory.** This imbalance is evident in Figure 6.19A by the length of the arrows—longer arrows (stronger force) representing the PGF and shorter arrows (weaker force) for the CF. Recall that the Coriolis force is weaker when winds are slower but stronger when winds are faster, so a weaker Coriolis force equates to a slower wind speed. Thus, winds around a low pressure in the upper atmosphere that are slower than the geostrophic wind—which flows in a straight line—are called *subgeostrophic* winds. Stated another way, when the pressure gradients are equal, curved isobars (gradient wind) will produce a slower wind around a low than would result from straight flow (geostrophic wind).

> The gradient wind is a better approximate of the airflow around curved paths than is the geostrophic wind.

Eye on the Atmosphere 6.1

In May and June 2011, the Wallow Fire burned more than 538 thousand acres (840 square miles) in southeastern Arizona. It was the largest wildfire in Arizona history.

Apply What You Know

1. Can you suggest two ways in which wind sustains wildfires such as this?

The opposite situation exists in anticyclonic flows, where the inward-directed Coriolis force must balance the pressure gradient force as well as provide the inward acceleration needed to turn the air. Therefore, in anticyclonic flow, the Coriolis force must be stronger than the pressure gradient force (Figure 6.19B), which means the wind speeds must be higher. For the same reason, upper-air winds around a high pressure are faster than the geostrophic wind, so they are called *supergeostrophic* winds.

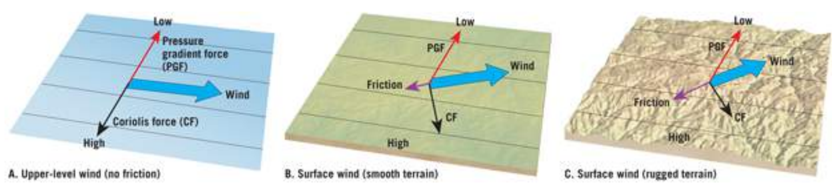
> In the upper atmosphere, winds blow more slowly around a low and faster around a high.

Surface Winds

Friction as a factor affecting wind is important only within the first 1.5 kilometers of Earth’s surface (Figure 6.20A). We know that friction acts to slow the movement of air. By slowing air movement, friction also reduces the Coriolis force, which is proportional to wind speed. Because the pressure gradient force is not affected by wind speed, it wins the tug-of-war against the Coriolis force, as shown in Figure 6.20B. The result is the movement of air *at an angle* across the isobars, toward the area of lower pressure.

Figure 6.20 Winds aloft versus surface winds

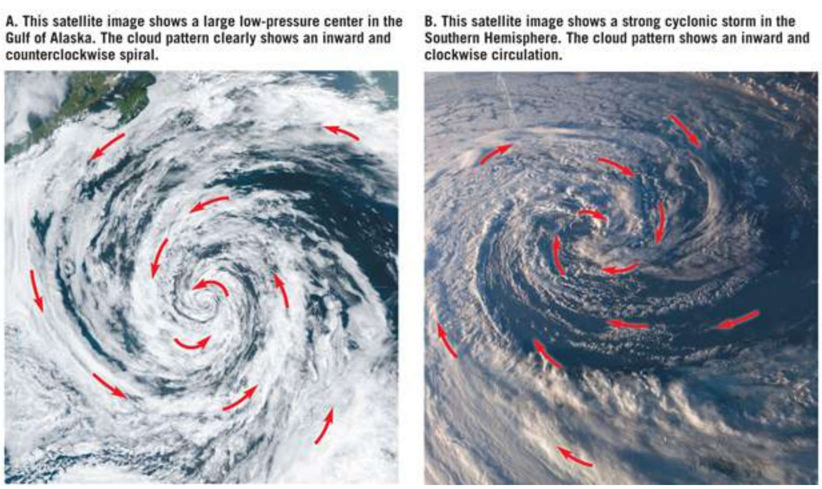
A, B. Comparison between upper-level winds and surface winds, showing the effects of friction on airflow. Friction slows surface wind speed, which weakens the Coriolis force, causing the winds to cross the isobars. **C.** Notice that over rugged terrain, wind speed is slower and directed at a steeper angle across the isobars than winds over smooth terrain.



The roughness of the surface determines the angle at which the air will flow across the isobars and influences the speed at which it will move. Over relatively smooth surfaces, where friction is low, air moves at an angle of 10° to 20° to the isobars and at speeds roughly two-thirds of geostrophic flow (Figure 6.20B). Over rugged terrain where friction is high, the angle can be as great as 45° from the isobars, with wind speeds reduced by as much as 50 percent (Figure 6.20C). We have learned that above the friction layer in the Northern Hemisphere, winds blow counterclockwise around a cyclone and clockwise around an anticyclone, with winds nearly parallel to the isobars. Combined with the effect of friction, we find that surface airflow crosses the isobars at varying angles, depending on the terrain, but always from higher to lower pressure (see Figure 6.6 and Box 6.2). In a cyclone, in which pressure decreases inward, friction causes a net flow *toward* its center. In an anticyclone, the opposite is true: Pressure decreases outward, and friction causes a net flow *away* from the center. Therefore, the resulting surface winds blow into and counterclockwise about a cyclone (Figure 6.21A) and outward and clockwise about an anticyclone. Of course, in the Southern Hemisphere the Coriolis force deflects the winds to the left and reverses the direction of flow (Figure 6.21B). Regardless of hemisphere, however, friction causes a net inflow of air around a cyclone and a net outflow around an anticyclone.

Figure 6.21 Cyclonic circulation in the Northern and Southern Hemispheres

The cloud patterns in these images allow us to see the circulation pattern in the lower atmosphere.



Box 6.2

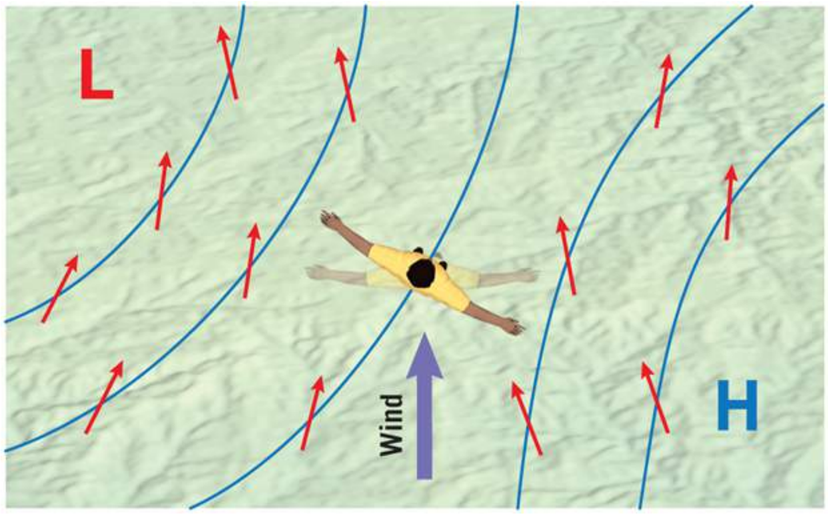
Buys Ballot's Law

As we have seen, wind direction is directly linked to the prevailing pressure pattern. Therefore, if we know the wind direction, we can also establish a rough approximation of the pressure distribution. This rather straightforward relationship between wind direction and pressure distribution was first formulated by the Dutch meteorologist Buys Ballot in 1857. Essentially, Buys Ballot's law states that in the Northern Hemisphere, *if you stand with your back to the wind, low pressure will be found to your left and high pressure to your right.* In the Southern Hemisphere, the situation is reversed. This can be easily verified for airflow aloft by examining Figure 6.20.

Although Buys Ballot's law is reliable for airflow aloft, it must be modified when applied to winds at the surface, where friction and topography interfere with the idealized circulation. At the surface, if you stand with your back to the wind and then turn clockwise about 30°, low pressure will be to your left and high pressure to your right (Figure 6.C).

Figure 6.C Illustration of Buys Ballot's Law

In the Northern Hemisphere, if you stand with your back to the wind, low pressure will be found on your left and high pressure on your right.



Apply What You Know

1. Explain why Buys Ballot's law would not apply in mountainous terrain.

> Friction causes winds at the surface to blow at an angle across the isobars and from areas of high pressure toward areas of lower pressure.

Concept Checks 6.4

■ Explain the formation of geostrophic wind, and describe how geostrophic wind blows in relation to isobars.

■ Unlike winds aloft, surface winds generally cross the isobars. Explain what causes this difference.

■ Prepare a diagram with isobars and wind arrows that shows the winds associated with surface cyclones and anticyclones in both the Northern and Southern Hemispheres.

*The tendency of a particle to move in a straight line when rotated creates an imaginary outward force called *centrifugal force*.

** Note that centripetal acceleration is important in establishing curved flow aloft, but near the surface, friction comes into play and greatly overshadows this much weaker force.

6.5 How Winds Generate Vertical Air Motion

LO 5 Sketch a diagram of the airflow around a low-pressure center (cyclone) and a high-pressure center (anticyclone), and describe the weather associated with each.

So far we have discussed wind without regard to how airflow in one region might affect airflow elsewhere. A researcher once commented that a butterfly flapping its wings in South America can generate a tornado in the United States. Although this is an exaggeration, it suggests that airflow in one region might cause a change in weather at some later time at a different location.

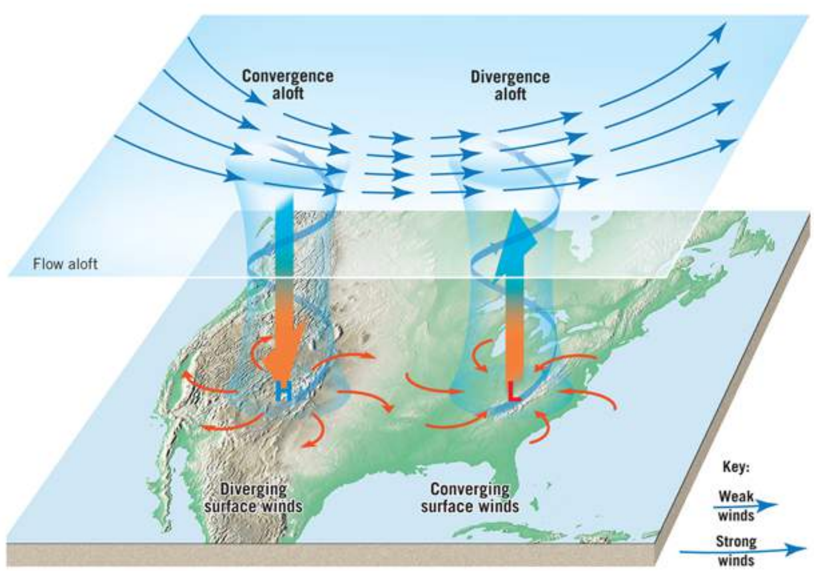
Just how horizontal airflow (wind) relates to vertical flow is an important issue. Although the rate at which air ascends or descends (except in violent storms) is slow compared to horizontal flow, it is very important as a weather maker. You learned in Chapter 4 that rising air is associated with cloudy conditions and often precipitation, whereas subsidence produces adiabatic heating and clearing conditions. In this section we examine how winds can create pressure changes and hence generate vertical airflow.

Vertical Airflow Associated with Cyclones and Anticyclones

Let us first examine a surface low-pressure system (cyclone) in which the air is spiraling inward. This net inward transport causes air molecules to compact into a smaller area, a process called *convergence* (Figure 6.22). Whenever air converges horizontally, it piles up—that is, it increases in mass as the area it occupies decreases. This process generates a "denser" air column. We have encountered a paradox: Low-pressure centers cause a net accumulation of air, which increases their pressure. Consequently, a surface cyclone should quickly eradicate itself, not unlike what happens to the vacuum in a coffee can when it is opened.

Figure 6.22 Airflow associated with cyclones (L) and anticyclones (H)

A low, or cyclone, has converging surface winds and rising air, resulting in cloudy conditions and often precipitation. A high, or anticyclone, has diverging surface winds and descending air, which leads to clear skies and fair weather.



Watch **Animation: Cyclones and Anticyclones**

You can see that for a surface low to exist, there must be compensation aloft. For example, surface convergence can be maintained if *divergence* (spreading out) of air aloft occurred at a rate equal to, or greater than, the inflow below. Figure 6.22 illustrates the relationship between surface convergence (inflow) and the divergence aloft (outflow) needed to maintain a low-pressure center. Notice that unlike surface flow, the air aloft generally flows from west to east along sweeping curves. As shown in Figure 6.22, divergence aloft occurs when the amount of air flowing away from the zone of divergence exceeds the amount of air blowing into this zone. Divergence aloft may even exceed surface convergence, thereby accelerating vertical motion and intensifying surface inflow. Because rising air often results in cloud formation and precipitation, the passage of a low-pressure center is generally accompanied by “bad weather.”

> Surface convergence and upper-level divergence cause rising motion, whereas surface divergence and upper-level convergence cause sinking motion.

Like their cyclonic counterparts, anticyclones must also be maintained from above. Outflow near the surface is accompanied by convergence aloft and general subsidence of the air column (Figure 6.22). Because descending air is compressed and warmed, cloud formation and precipitation are less likely in an anticyclone. Thus, fair weather can usually be expected with the approach of a high-pressure system.

For these reasons, it is common to see “stormy” at the low-pressure end of household barometers and “fair” at the high end. By noting the pressure trend—rising, falling, or steady—we have a good indication of the approaching weather. Such a determination, called the *pressure tendency*, or *barometric tendency*, is useful in short-range weather prediction. The generalizations relating cyclones and anticyclones to weather conditions (Figure 6.23) are stated nicely in this verse (where “glass” refers to a barometer):

When the glass falls low,
Prepare for a blow;
When it rises high,
Let all your kites fly.

Figure 6.23 **Basic weather generalizations associated with pressure centers**

A. A rainy day in London. Low-pressure systems are frequently associated with cloudy conditions and precipitation. **B.** By contrast, clear skies and "fair" weather may be expected when an area is under the influence of high pressure.

It is obvious why local television weather broadcasters emphasize the positions and projected paths of cyclones and anticyclones. The "villain" on these weather programs is always the low-pressure system, which produces "foul" weather in any season. Lows move in roughly a west-to-east direction across the United States and require a few days to more than a week for the journey. Because their paths can be erratic, accurately predicting their migration is difficult, but it is essential for short-range forecasting. Meteorologists must also determine whether the flow aloft will intensify an embryo storm or suppress its development.

Other Factors Promoting Vertical Airflow

Vertical motion in the atmosphere is very closely tied to our daily weather. Other factors besides upper-level convergence and divergence also affect vertical motion.

Friction can cause both convergence and divergence. When air moves from the relatively smooth ocean surface to land, for instance, the increased friction causes an abrupt drop in wind speed. This reduction of wind speed downstream results in a pileup of air upstream. Thus, converging winds and ascending air accompany flow from the ocean to the land. This effect contributes to lake-effect snow in the winter and to the cloudy conditions over the humid coastal regions of Florida. Conversely, when air moves from the land to the ocean, general divergence and subsidence accompany the seaward flow of air because of reduced friction and increasing wind speed over the water. The result is often subsidence and clearing conditions.

Mountains also hinder the flow of air and cause divergence and convergence. As air passes over a mountain range, it is compressed vertically, producing horizontal spreading (divergence) aloft. Air reaching the leeward side of the mountain experiences vertical expansion, which causes convergence aloft. This effect greatly influences the weather in the United States east of the Rocky Mountains, as we shall examine later.

The connections between surface conditions and those aloft have led to significant research on understanding atmospheric circulation, especially in the midlatitudes. After we examine global atmospheric circulation in Chapter 7, we will again consider the relationships between horizontal airflow (wind) and vertical motions (rising and descending air currents).

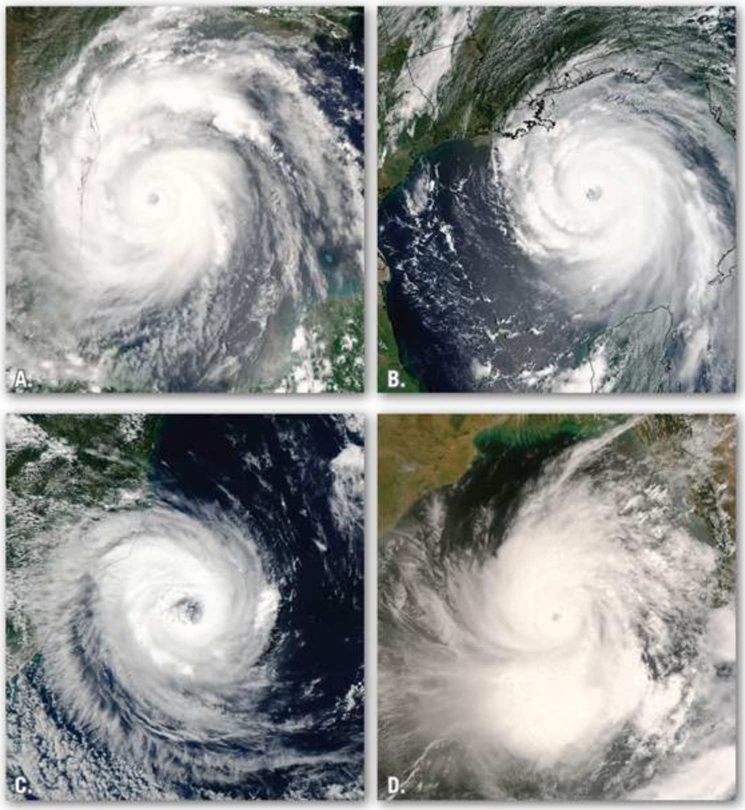
You might have wondered . . .

What causes "mountain sickness"?

When visitors hike at elevations above 3000 meters (10,000 feet), they typically become tired and short of breath. These symptoms are caused by breathing air with roughly 30 percent less oxygen than at sea level. At these altitudes, our bodies try to compensate for oxygen deficiency by breathing more deeply and increasing the heart rate, thereby pumping more blood to the body's tissues. The additional blood is thought to cause brain tissues to swell, resulting in headaches, insomnia, and nausea—the main symptoms of *acute mountain sickness*. Mountain sickness usually can be alleviated with a night's rest at a lower altitude, but some people suffer from *high-altitude pulmonary edema*, a buildup of fluid in the lungs that requires prompt medical attention.

Eye on the Atmosphere 6.2

These satellite images show four different tropical cyclones (hurricanes) that occurred on different dates in different parts of the world.



Apply What You Know

1. For each storm, examine the cloud pattern and determine whether the flow is clockwise or counterclockwise.
2. In which hemisphere is each storm located, Northern or Southern?

Concept Checks 6.5

- For surface low pressure to exist for an extended period, what condition must exist aloft?
- What general weather conditions can we expect when surface pressure is rising? When the surface pressure is falling?
- Converging winds and ascending air are often associated with the flow of air from the oceans onto land. Conversely, divergence and subsidence often accompany the flow of air from land to sea. What causes this convergence over land and divergence over the ocean?

6.6 Wind Measurement

LO 6 Define *prevailing wind* and explain how wind direction is expressed.

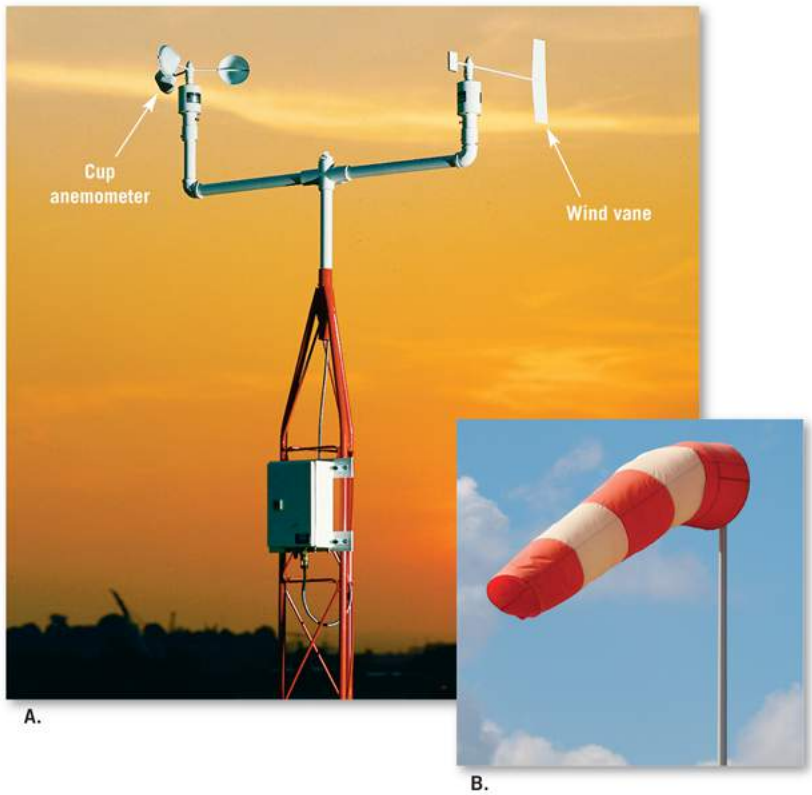
Two basic wind measurements—direction and speed—are important to weather observers.

Measuring Wind Direction

Winds are always labeled by the direction *from* which they blow. A north wind blows from the north toward the south; an east wind blows from the east toward the west. One instrument commonly used to determine wind direction, the **wind vane**, is often seen on the tops of buildings (Figure 6.24A). Sometimes the wind direction is shown on a dial connected to the wind vane. The dial indicates the direction of the wind either by points of the compass—that is, N, NE, E, SE, and so on—or by a scale of 0° to 360°. On the latter scale, 0° (or 360°) is a wind coming from the north, 90° is from the east, 180° is from the south, and 270° is from the west.

Figure 6.24 Wind measurement

A. Wind vane (right) and cup anemometer (left). The wind vane shows wind direction, and the anemometer measures wind speed. **B.** A wind sock is a device for determining wind direction and estimating wind speed. Wind socks are common sights at small airports and landing strips.

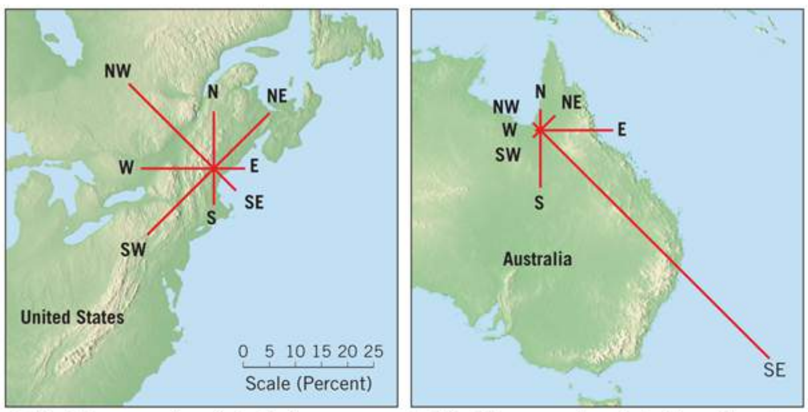


> Winds are labeled by the direction *from* which they blow.

When the wind consistently blows more often from one direction than from any other, it is called a **prevailing wind**. You may be familiar with the prevailing *westerlies* that dominate midlatitude circulation. In the United States, for example, these winds consistently move the "weather" from west to east across the continent. Embedded within this general eastward flow are cells of high and low pressure, with their characteristic clockwise and counterclockwise flows. As a result, the winds associated with the westerlies, as measured at the surface, often vary considerably from day to day and from place to place. A *wind rose* provides a way to represent prevailing winds by indicating the percentage of time the wind blows from various directions (Figure 6.25). The length of the lines on the wind rose indicates the percentage of time the wind blew from that direction. As seen in Figure 6.25B, the southeasterly direction of airflow associated with the belt of trade winds is much more consistent than the westerlies (Figure 6.25A.)

Figure 6.25 Wind roses

The percentage of directional windflow is charted on a *wind rose* and may represent daily, weekly, monthly, seasonal, or annual totals. **A.** Westerly winds prevail in the midlatitudes. **B.** Southeasterly winds dominate in subtropical latitudes.



A. Wind frequency for winter in the northeastern United States.

B. Wind frequency for winter in northeastern Australia. Note the reliability of the southeast trade winds in Australia as compared to the westerlies in the northeastern United States.

Knowledge of the wind patterns for a particular area can be useful. For example, when an airport is constructed, the runways are aligned with the prevailing wind to assist in takeoffs and landings. Furthermore, prevailing winds greatly affect a region's weather and climate. Mountain ranges that trend north–south, such as the Cascade Range of the Pacific Northwest, cause the ascent of the prevailing westerlies. Thus, the windward (west) slopes of these ranges are rainy, whereas the leeward (east) sides are dry.

Measuring Wind Speed

Wind speed is often measured with a **cup anemometer**, which has a dial much like the speedometer of an automobile (Figure 6.24A). Sometimes an **aerovane** is used instead of a wind vane and cup anemometer. As illustrated in Figure 6.26, this instrument resembles a wind vane with a propeller at one end. The fin keeps the propeller facing into the wind, allowing the blades to rotate at a rate proportional to the wind speed. This instrument is commonly attached to a recorder that produces a continuous record of wind speed and direction. This information is valuable for determining locations where winds are steady and speeds are relatively high—potential sites for tapping wind energy (Box 6.3).

Figure 6.26 Aerovane

This aerovane is located in a remote location and measures wind speed and direction, which is transmitted to a central location for processing.

Box 6.3

Wind Energy

Air has mass, and when it moves, it has energy of motion—kinetic energy. A portion of that energy can be converted into mechanical energy or electricity, both of which power our modern society.

Mechanical energy from wind was commonly used for pumping water and grinding wheat and corn until the advent of readily available electrical energy, and the farm windmill is still a familiar sight in many rural areas. By contrast, modern wind-powered electric turbines generate electricity for homes, businesses, and manufacturing (Figure 6.D). Global wind-generating capacity has been doubling every 3 years. According to the Global Wind Energy Council, at the end of 2016 China led the world in installed wind-generation capacity, followed by the United States, Germany, and India.

Figure 6.D Modern wind farm

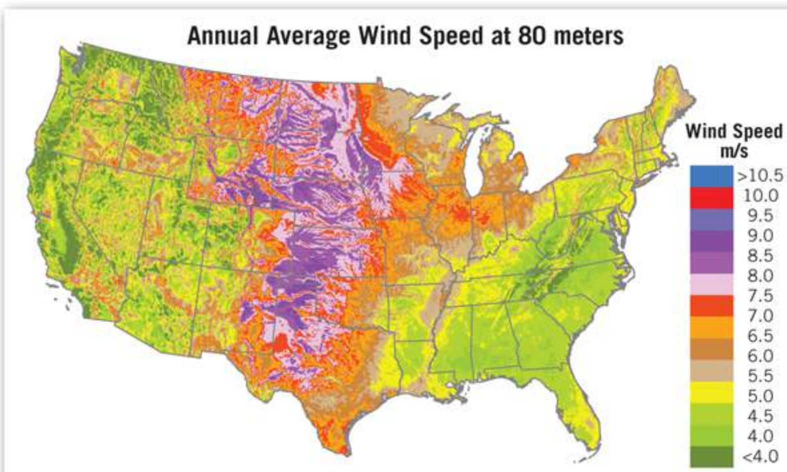
These wind turbines are operating near Tehachapi Pass, Kern County, California. California was the first state to develop significant wind power, although it has now been surpassed by Texas.

Wind speed is crucial in determining whether a place is a suitable site for a wind-energy facility. Generally, a minimum average wind speed of about 6 meters per second (13 miles per hour) is necessary for a large-scale wind-power facility to be profitable. A small difference in wind speed results in a large difference in energy production and, therefore, a large difference in the cost of the electricity generated. For example, a turbine operating on a site with an average wind speed of 13 miles per hour generates roughly 30 percent more electricity than one operating at 12 miles per hour.

Although the modern U.S. wind industry began in California, many states have greater wind potential. Figure 6.E shows the estimated average wind speeds at a height of 80 meters (260 feet) above the surface—the level that most commercial wind turbines operate. Areas with average wind speeds greater than about 6 meters per second (13 miles per hour) are considered to have potential for development. According to the American Wind Energy Association, at the end of 2016, Texas (20,321 megawatts, MW) had the most installed wind capacity, followed by Iowa (6,917 MW), Oklahoma (6,645 MW), and California (5,662 MW).*

Figure 6.E The wind energy potential for the United States

Large wind systems require average wind speeds of about 6 meters per second (13 miles per hour).



Compared to burning fossil fuels to generate electricity, wind power produces minimal air pollution. However, problems related to wind energy include significant injuries and deaths to birds. Noise and visual impact are also cited as environmental issues.

The U.S. Department of Energy currently provides funds to develop offshore wind technologies. Offshore winds are abundant, stronger, and blow more consistently than winds over land. Data suggest that more than 4 million megawatts (MW) of capacity is available on public land along the coasts off the United States and the Great Lakes. This is four times more than the total electrical generating capacity of the United States. Unfortunately, development of many of these sites is unlikely because of the public's reluctance to dot scenic coastal land with wind turbines.

Apply What You Know

1. What country has the largest wind-generating capacity?
2. List environmental issues associated with the production of wind energy.

At small airstrips, *wind socks* are frequently used (Figure 6.24B). A wind sock consists of a cone-shaped bag that is open at both ends and free to change position with shifts in wind direction. The degree to which the sock is inflated indicates the strength of the wind.

Recall that 70 percent of Earth's surface is covered by water, a fact that makes conventional methods of measuring wind speed difficult. Weather buoys and ships at sea provide limited coverage, but the availability of satellite-derived wind data has dramatically improved weather forecasts. One example is an instrument that NASA has attached to the International Space Station to measure ocean surface wind speed and direction, which will help improve weather forecasts, including hurricane monitoring.

Measuring the speed and direction of winds aloft is also important. Upper-level flow can be established using satellite images to track cloud movements, and **rawinsondes**, which are radiosondes tracked by radar, allow us to calculate airflow at several levels of the atmosphere.

Concept Checks 6.6

- A southwest wind blows from the ________(direction) toward the ________(direction).
- When the wind direction is 315°, from what compass direction is it blowing?
- Describe the instruments used to measure wind speed.

*One megawatt (MW) is enough electricity to supply 240–400 American households.

Concepts in Review

6.1 Atmospheric Pressure and Wind

LO 1 Define *atmospheric pressure* and explain how it is displayed on a weather map.

Key Terms

wind
atmospheric pressure (air pressure)
millibar (mb)
sea-level pressure
mercury barometer
barometric pressure
aneroid barometer
station pressure
isobar
anticyclone
cyclone (midlatitude cyclone)
ridge
trough

- Wind, the horizontal movement of air, is a result of horizontal differences in air pressure.
- Air pressure is the force exerted at a location by the weight of air above. Average air pressure at sea level is about 14.7 pounds per square inch, or 1013.25 millibars, or 29.92 inches of mercury.
- Two instruments used to measure atmospheric pressure are the mercury barometer and the aneroid barometer.
- Atmospheric pressure is displayed on surface weather maps using isobars—lines connecting places of equal pressure. On upper-level weather charts, height contours are used. Higher-elevation contours indicate higher pressures, and lower-elevation contours indicate lower pressures.

6.2 Why Does Air Pressure Vary?

LO 2 Identify the factors affecting air pressure at Earth's surface as well as aloft.

Key Terms

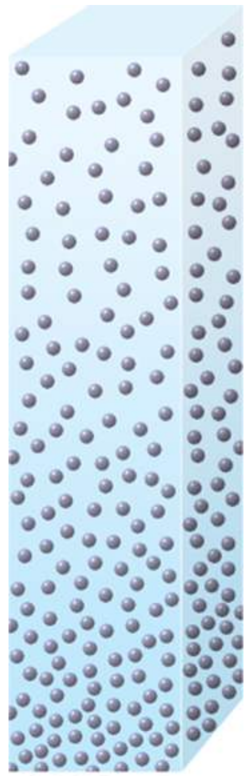
U.S. standard atmosphere

hydrostatic balance

convergence

divergence

- The pressure at any given altitude is equal to the weight of the air above that point.
- Two factors that largely determine the pressure exerted at the surface by an air mass are temperature and humidity.
- Temperature differences cause horizontal pressure differences, which produce a force (pressure gradient force) that causes air to flow from areas of high pressure to areas of low pressure.


1013 mb

6.3 Factors Affecting Wind

LO 3 List and describe the three forces that act on the atmosphere to either create or alter winds.

Key Terms

pressure gradient force (PGF)

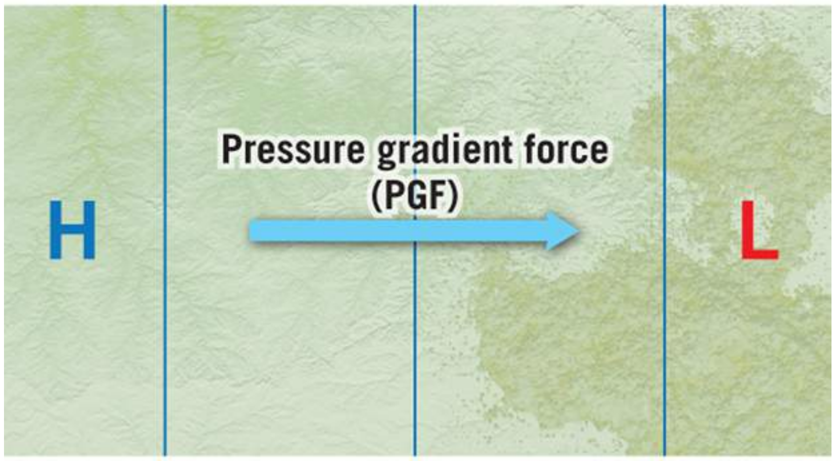
pressure gradient

Coriolis force

friction

boundary layer

- Wind is controlled by a combination of (1) the pressure gradient force, (2) the Coriolis force, and (3) friction.
- The pressure gradient force is the primary driving force of wind resulting from pressure differences. On a map, closely spaced isobars (lines of equal pressure) indicate a steep pressure gradient and strong winds; widely spaced isobars indicate a weak pressure gradient and light winds.
- The Coriolis force produces a deviation in the path of wind due to Earth's rotation (to the right in the Northern Hemisphere and to the left in the Southern Hemisphere).
- The force of friction significantly influences airflow near Earth's surface but is negligible above a height of a few kilometers.



Pressure gradient force
(PGF)
H
L

6.4 Winds Aloft Versus Surface Winds

LO 4 Explain why winds aloft flow roughly parallel to the isobars, whereas surface winds travel at an angle across the isobars.

Key Terms

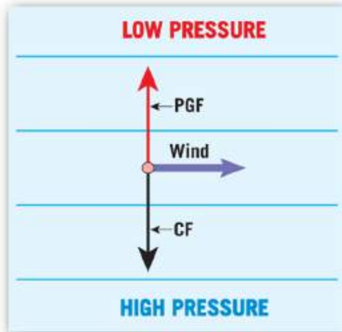
geostrophic wind

gradient wind

cyclonic flow

anticyclonic flow

- Above a height of a few kilometers, geostrophic winds are generated when a balance is reached between the pressure gradient force and the opposing Coriolis force.
- Winds that blow at a constant speed parallel to curved isobars are termed gradient winds. In low-pressure systems such as midlatitude cyclones, the circulation of air is termed cyclonic flow. Cyclonic flow is counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere.
- Centers of high pressure, called anticyclones, exhibit anticyclonic flow, which is clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere.
- Near Earth's surface, friction plays a major role in determining the direction of airflow. The result is a movement of air at an angle across the isobars, toward the area of lower pressure. The resulting winds blow into and counterclockwise around a Northern Hemisphere surface cyclone. In a Northern Hemisphere surface anticyclone, winds blow outward and clockwise.


LOW PRESSURE
PGF
Wind
CF
HIGH PRESSURE

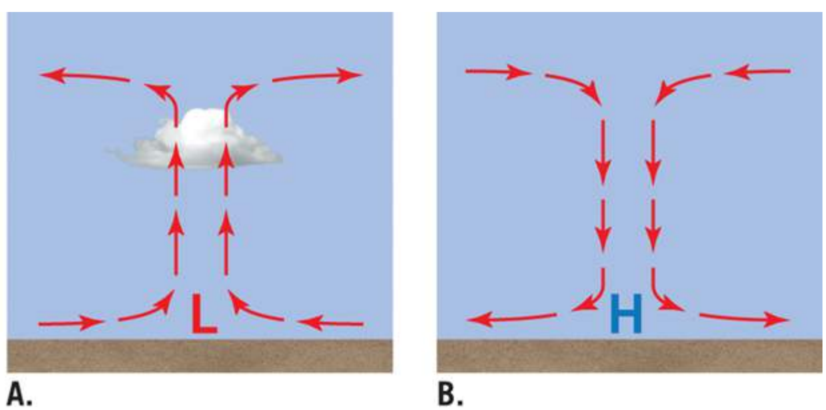
6.5 How Winds Generate Vertical Air Motion

LO 5 Sketch a diagram of the airflow around a low-pressure center (cyclone) and a high-pressure center (anticyclone), and describe the weather associated with each.

Key Term

pressure tendency (barometric tendency)

- A surface low-pressure system (or cyclone) with its associated horizontal convergence (compaction of air) is maintained or intensified by divergence (spreading out) aloft.
- Fair weather can usually be expected with the approach of a high-pressure system or anticyclone because of the sinking air caused by upper-level convergence and surface divergence.



6.6 Wind Measurement

LO 6 Define *prevailing wind* and explain how wind direction is expressed.

Key Terms

wind vane

prevailing wind

cup anemometer

aerovane

rawinsonde

- Two basic wind measurements—direction and speed—are measured and recorded as part of daily weather maps. Winds are always labeled by the direction from which they blow.
- Anemometers measure wind speed; wind vanes measure wind direction; aerovanes and satellites measure both wind speed and direction.

Exercises and Online Activities

Mastering Meteorology™

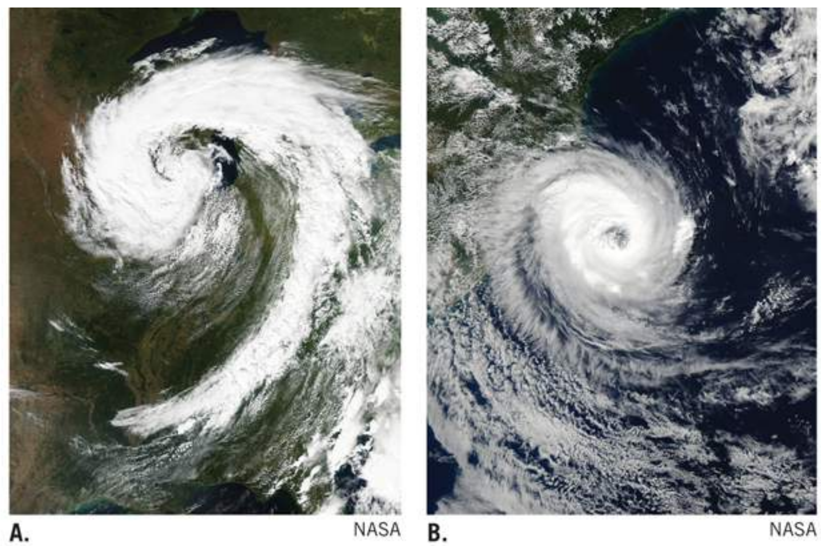
For instructor-assigned homework, test prep resources, and other learning materials, visit **Mastering Meteorology.**

Review Questions

1. What is air pressure, and how is it measured?
2. In what units is pressure usually plotted on a weather map?
3. Explain how atmospheric pressure changes with altitude.
4. How is station pressure different from sea-level pressure?
5. What is meant by the 500-millibar surface? Why is this useful for meteorologists?
6. Which exerts more pressure, dry or moist air? Explain.
7. Define the pressure gradient force (PGF). What role does the pressure gradient force play in creating wind?
8. In the absence of other forces, which way would wind blow?
9. Explain how the Coriolis force works, using a north-to-south example and a west-to-east example.
10. Compare the geostrophic wind to the gradient wind.
11. What direction does the wind blow around a surface high-pressure system in the Northern Hemisphere? Around a low-pressure system?
12. Does the wind blow faster around a low in the upper atmosphere or around a high? Explain.
13. What two forces are in equilibrium when the atmosphere is in geostrophic balance?
14. What effect does friction have on wind speed and direction?
15. What type of weather is generally associated with a surface high pressure? Surface low pressure?
16. What is meant by *prevailing wind*?
17. Describe two ways to measure winds.

Give It Some Thought

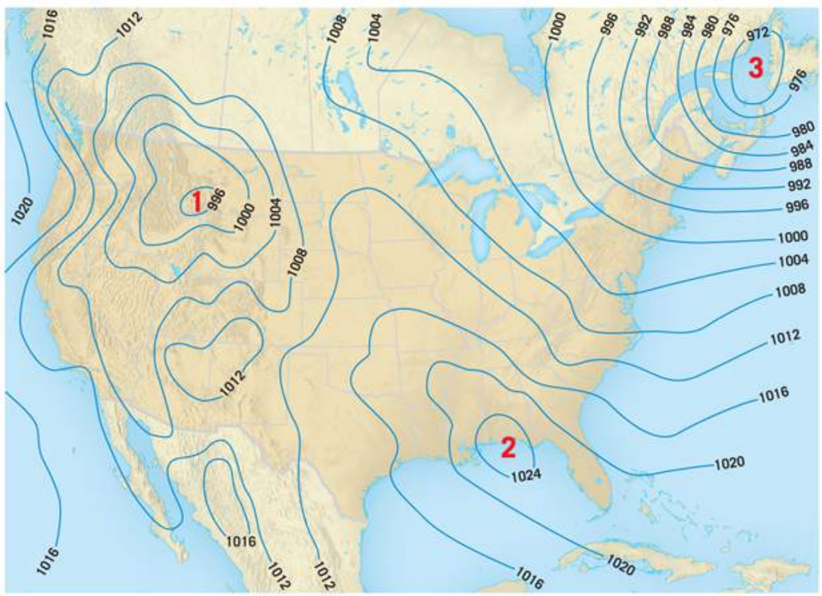
1. The accompanying satellite images show the cloud patterns associated with two cyclones (low-pressure systems).



   a. Determine the airflow around each of these pressure cells (clockwise or counterclockwise).
   b. Which of these is located in the Northern Hemisphere?
   c. Can you identify which one of these storm systems is a tropical cyclone (hurricane)? (*Hint:* Compare these images to Figure 11.11.)
2. Given the following descriptions, identify the direction (for example, east, west, northwest) in which the Coriolis force is acting on the moving object.
   a. A commercial jet flying from New York to Chicago
   b. A baseball thrown from south to north in South Dakota
   c. A blimp floating from St. Louis northeast toward Detroit
   d. A boomerang thrown from west to east in Australia
   e. A football thrown along the equator
3. If a weather system with strong winds approached Lake Michigan from the west, how might the speed of the winds change as the

system traversed the lake? Explain your answer.

4. The accompanying map is a simplified surface weather map for April 2, 2011, on which the centers of three pressure cells are numbered.
    - a. Which of the pressure cells are anticyclones (highs), and which are cyclones (lows)?
    - b. Which pressure system has the steepest pressure gradient and, hence, exhibits the strongest winds?
    - c. Refer to Figure 6.2 to determine whether pressure system 3 should be considered strong or weak.



5. If you live in the Northern Hemisphere and are directly west of the center of a midlatitude cyclone, what is the probable wind direction?
6. Given the following time line of barometric pressure readings, interpret the *likely* weather conditions, specifically cloudiness and precipitation, for each of the following days:

Day 1: Pressure steady at 1025 millibars

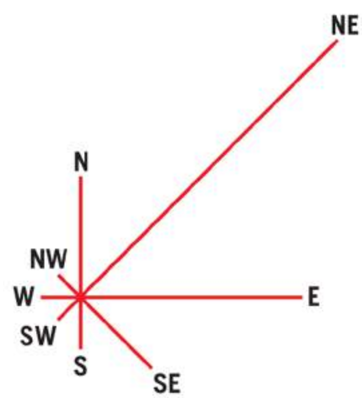
Day 2: Pressure at 1010 millibars and falling

Day 3: Pressure reaches a 4-day minimum of 992 millibars

Day 4: Pressure at 1008 millibars and rising

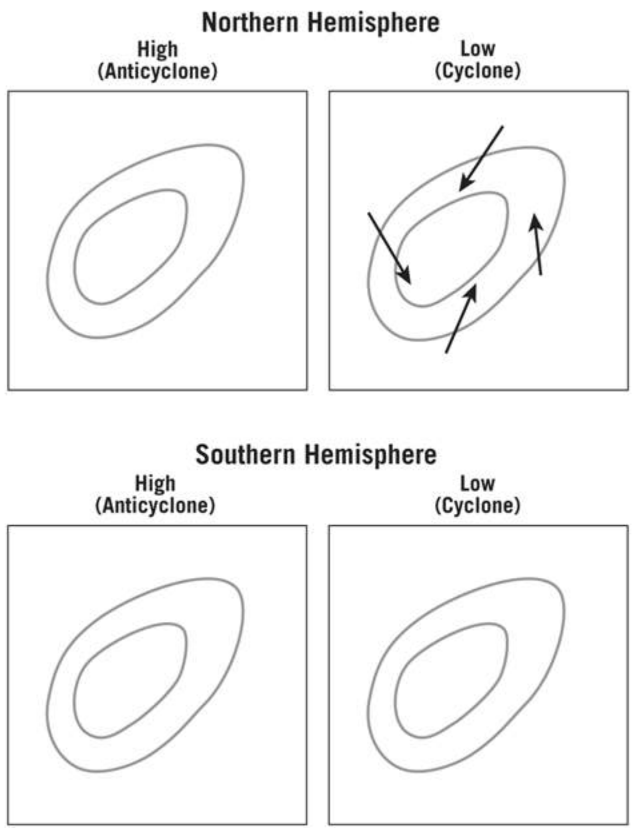
7. If you wanted to erect wind turbines to generate electricity, would you search for a location that typically experiences a strong pressure gradient or a weak pressure gradient? Explain.

8. When an airport is designed, it is important to have the runways positioned so that planes take off into the wind. Refer to the accompanying wind rose, and discuss the orientation of the runway and the direction the planes would travel when they take off.



9. You and a friend are watching TV on a rainy day when the weather reporter states, “The barometric pressure is 28.8 inches and rising.” Hearing this, you say, “It looks like fair weather is on its way.” How would you respond if your friend asked the following questions?
    a. “I thought air pressure had something to do with the weight of air. How does ‘inches’ relate to weight?”
    b. “Why do you think the weather is going to improve?”

10. Use the accompanying diagram to show the wind directions associated with high- and low-pressure cells in both hemispheres. The diagram for a low-pressure system in the Northern Hemisphere is already completed. Add arrows to show the wind in the other pressure cells.



By the Numbers

1. Figure 6.3 illustrates a simple mercury barometer. When a glass tube is completely evacuated of air and placed into the dish of mercury, the mercury rises to a height such that the force of the air pushing on the open dish matches the gravity pulling the mercury back down the tube. The density of mercury is 13,534 kilograms per cubic meter, which means that mercury is very dense compared to water (1000 kilograms per cubic meter). In the mercury barometer, the mercury will rise to 29.92 inches under standard sea-level pressure. How tall would the barometer need to be if you used water instead of mercury?
2. Average air pressure at sea level is about 14.7 pounds per square inch. Using this information, how much does the entire atmosphere weigh? (*Hint:* The radius of Earth is 3963 miles.)

Beyond the Textbook

1. Wind Patterns and Weather

Go to https://earth.nullschool.net/ to explore how wind at different pressure levels influences weather.

1. Where are wind speeds faster (longer lines and brighter yellow/green colors), over land or over water? Why do you think this is the case?
2. Are winds generally stronger in the Northern Hemisphere or the Southern Hemisphere? Why do you think this is the case?

Click on the word "earth" in the bottom left of the image, and gradually change the "Height" (pressure level in millibars—labeled "hPa") to observe winds at different altitudes. Recall that lower pressures correspond to higher altitude.

3. At what pressure level are winds strongest? Why do you think the winds are strongest at this elevation and not higher or lower?
4. Winds direct the movement of weather systems. From what general direction do the winds, and therefore weather systems, originate in the midlatitudes?
5. How are the winds at the 70-mb and 10-mb height level different from the winds directly below these levels? What layer of the atmosphere are the winds at these levels?

Now rotate the globe by clicking and dragging on it so you can see the wind field in other parts of the world.

6. Describe the general wind direction in the North Atlantic between North America and Europe. How does it compare to the wind direction between Northern Africa and South America?

You can explore this animation further by overlaying the wind pattern with data for temperature (TEMP), relative humidity (RH), total precipitable water (TPW), total cloud water (TCW), and misery index (MI).

7. On this date, what areas have high concentrations of total precipitable water (TPW)? How do these areas compare to areas of total cloud water (TCW)?
8. Describe a location that has a high misery index (MI)—either wind chill or heat index.

2. Misconceptions about the Coriolis Force

Go to the Snopes web page on the Coriolis force at http://www.snopes.com/science/coriolis.asp.

1. Describe the myth about the Coriolis force discussed on the web page.
2. Explain why this myth is false.

Chapter 7 Circulation of the Atmosphere

These wind-driven waves are pounding the coastal village of Sainte-Luce, Quebec.

Focus on Concepts

Each statement represents the primary learning objective for the corresponding major heading within the chapter. After you complete the chapter, you should be able to:

1. Distinguish microscale, mesoscale, and macroscale winds, and give an example of each (7.1).
2. List five types of local winds and describe their formation (7.2).
3. Sketch and describe the three-cell model of global circulation (7.3).
4. Summarize Earth's idealized zonal pressure and precipitation belts. Describe how continents and seasonal temperature changes complicate the idealized pattern (7.4).
5. Explain why the airflow aloft in the middle latitudes has a strong west-to-east component (7.5).
6. Explain the origin of the polar jet stream and its relationship to midlatitude cyclonic storms (7.6).
7. Sketch and label the major ocean currents on a world map (7.7).
8. Describe the Southern Oscillation and its relationship to El Niño and La Niña. List climate impacts of El Niño and La Niña (7.8).

Pressure differences caused by unequal heating of Earth's surface generate the global wind system. These winds, which operate at various scales, blow in an unending attempt to balance these surface temperature differences. Because the zone of maximum solar heating migrates with the seasons—moving northward during the Northern Hemisphere summer and southward as winter approaches—the wind patterns that make up the general circulation also migrate latitudinally. This chapter focuses on models that describe the distribution of Earth's pressure zones that, in turn, generate the global wind system.

7.1 Scales of Atmospheric Motion

LO 1 Distinguish microscale, mesoscale, and macroscale winds, and give an example of each.

Earth's highly integrated wind system can be thought of as a series of deep rivers of air encircling the planet. Embedded in the main currents are vortices of various sizes, including midlatitude cyclones, hurricanes, tornadoes, and dust devils. Like eddies in a stream, these rotating wind systems develop and die out with somewhat predictable regularity.

Residents of the United States and Canada are familiar with the term *westerlies*, which describes winds that predominantly blow across the midlatitudes from west to east. However, over short time periods, the winds may blow from any direction. You may recall being in a storm when shifts in wind direction and speed came in rapid succession. With such variations, how can we describe our winds as westerly? The answer lies in our attempt to simplify descriptions of the atmospheric circulation by sorting out events according to *size* and the *time frame* in which the wind systems occur. On the scale of a weather map, for instance, where observing stations are spaced about 150 kilometers (nearly 100 miles) apart, small whirlwinds that carry dust skyward are far too small to be identified. Instead, weather maps reveal larger-scale wind patterns, such as those associated with traveling cyclones and anticyclones.

> Motions in the atmosphere vary in size from the tiniest wind gusts to wind systems that encircle the entire globe.

In general, large weather patterns persist longer than their smaller counterparts. For example, dust devils usually last a few minutes, but midlatitude cyclones typically take a few days to cross the United States and sometimes dominate the weather for a week or longer.

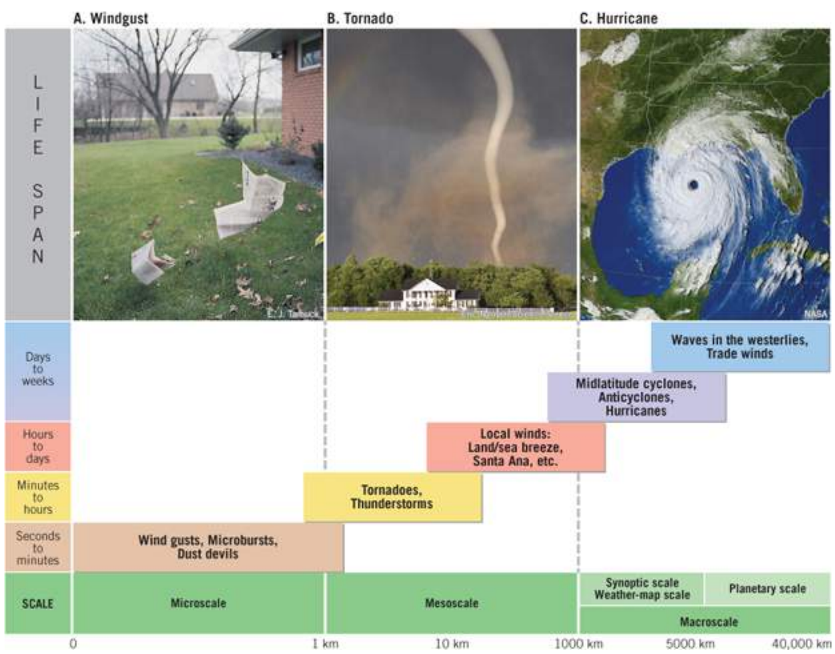
Keep in mind that motions in the atmosphere vary in size from the tiniest wind gusts to wind systems that encircle the globe. Meteorologists divide winds into the three categories of atmospheric circulation: microscale, mesoscale, and macroscale.

Microscale Winds

We call the smallest scale of air motion **microscale winds**. These small, often chaotic winds normally last for only seconds or at most minutes. Examples include simple gusts that hurl debris into the air (Figure 7.1A) and small, well-developed vortices such as dust devils. Although dust devils resemble tornadoes, they are much smaller and less intense than most tornadoes (Box 7.1).

Figure 7.1 **Three scales of atmospheric motion**

A. Gusts illustrate microscale winds. **B.** Tornado-producing supercell thunderstorms exemplify mesoscale wind systems. **C.** Satellite image of a hurricane, an example of macroscale circulation (weather-map scale).



Box 7.1

Dust Devils

Common in arid regions of the world are the whirling vortices called *dust devils* (Figure 7.A). Although they resemble tornadoes, dust devils are generally only a few meters in diameter and reach heights no greater than about 100 meters (300 feet). Further, these whirlwinds are usually short-lived phenomena that die out within minutes.

Figure 7.A Dust devil

Although these whirling vortices resemble tornadoes, they have a different origin and are much smaller and less intense.

Unlike tornadoes, which are associated with storm clouds, dust devils form on days when clear skies dominate and develop from the ground upward. Because surface heating is critical to their formation, dust devils occur most frequently in the afternoon, when surface temperatures are highest.

Recall that when the air near the surface is considerably warmer than the air a few dozen meters overhead, the layer of air near Earth's surface becomes unstable. In this situation, warm surface air begins to rise, causing air near the ground to be drawn into the developing whirlwind. The rotating winds associated with dust devils are produced by the same phenomenon that causes ice skaters to spin faster as they pull in their arms closer to their body. As the inwardly spiraling air rises, it carries sand, dust, and other loose debris dozens of meters into the air—making a dust devil visible.

Most dust devils are small and short-lived, but occasionally these whirlwinds grow to 100 meters or more in diameter and over a kilometer high. With wind speeds that may reach 100 kilometers (60 miles) per hour, large dust devils can do considerable damage.

Apply What You Know

1. Where do most dust devils form?
2. In what ways are dust devils different from tornadoes?

Not all wind systems fit neatly within one of the categories. For example, small tornadoes are considered microscale, whereas large tornadoes are classified as mesoscale winds.

Mesoscale Winds

Mesoscale winds generally last for a few minutes to several hours, and occasionally they last a few days. These middle-sized phenomena are often less than 100 kilometers (60 miles) across—but can be up to about 1000 km wide. They include strong updrafts and downdrafts, tornadoes, as well as few larger wind systems referred to as *local winds* (Figure 7.1B). Some mesoscale winds have a strong vertical component. For example, the strong downdrafts within thunderstorms have speeds exceeding 100 kilometers per hour and may be accompanied by heavy rain and hail that cause considerable damage. Tornadoes, the most destructive mesoscale winds, will be considered in Chapter 10. Tropical storms and small hurricanes are also considered mesoscale wind systems, but large hurricanes are classified as macroscale winds.

Macroscale Winds

The largest wind patterns, called **macroscale winds**, are divided into two categories: *planetary-scale* and *synoptic-scale*. **Planetary-scale winds** are exemplified by the westerlies and trade winds that carried sailing vessels back and forth across the Atlantic during the opening of the New World. These large-scale flow patterns extend around the entire globe and can remain essentially unchanged for weeks at a time.

The somewhat smaller macroscale circulation, called **synoptic-scale winds**—also known as *weather-map scale*—are about 1000 kilometers (600 miles) in diameter and are easily identified on weather maps. Two well-known synoptic-scale systems are the traveling *midlatitude cyclones* and *anticyclones* that appear on weather maps as areas of low and high pressure, respectively. These weather producers are confined largely to the middle latitudes.

> Winds are classified as microscale (smallest), mesoscale (intermediate), or macroscale (largest)—the latter of these is subdivided into planetary and synoptic-scale motions.

Wind Patterns on All Scales

Although it is common practice to divide atmospheric motions according to size, remember that global winds are a composite of motion on all scales—much like a meandering river that contains large eddies composed of smaller eddies containing still smaller eddies. As an example, we will examine winds associated with hurricanes that form over the North Atlantic. When we view one of these tropical cyclones on a satellite image, the storm appears as a large whirling cloud migrating slowly across the ocean (Figure 7.1C). From this perspective, which is at the weather-map (synoptic) scale, the general counterclockwise rotation of the storm is easily seen.

In addition to their rotating motions, hurricanes often move from east to west or northwest. (Once hurricanes move into the belt of the westerlies, they tend to change course and move in a northeasterly direction.) This motion demonstrates that these large eddies are embedded in a still larger flow (planetary scale) that is moving westward across the tropical portion of the North Atlantic.

When we examine a hurricane more closely by flying an airplane through it, some of the small-scale aspects of the storm become noticeable. As the plane approaches the outer edge of the system, it is evident that the large rotating cloud that we see in the satellite image consists of many individual cumulonimbus towers (thunderstorms). Each of these cumulonimbus clouds lasts for a few hours, and they must be continually replaced by new ones for the hurricane to persist. During the flight, we also realize that the individual thunderstorms are made up of even smaller-scale turbulences. The small thermals of rising and descending air in these clouds make for a rough flight.

Concept Checks 7.1

- List the three major categories of atmospheric circulation, and give at least one example of each.
- Describe how the size of a wind system is related to its duration (life span).
- Explain in your own words what is meant by the statement "Global winds are a composite of winds of all scales."

7.2 Local Winds

LO 2 List five types of local winds and describe their formation.

Local winds are examples of mesoscale winds—with a time frame of minutes to hours and 1 to 1000 kilometers in size. Most local winds are linked to temperature and pressure differences that result from variations in topography or in local surface conditions.

Recall that winds are named for the direction *from which they blow.* This holds true for local winds. Thus, a sea breeze originates over water and blows toward land, whereas a mountain breeze blows downslope, away from its source.

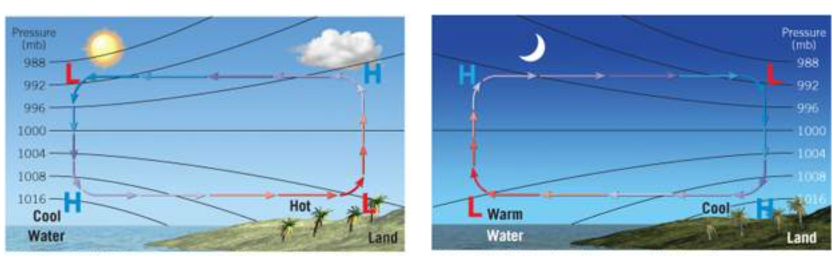
> Local winds are named for the direction from which they blow at the surface—a sea breeze blows from the sea toward the land.

Land and Sea Breezes

Land and sea breezes occur in coastal locations (near oceans or large lakes) in the tropics throughout the year as well as in the midlatitudes during the summer months. These local winds arise from differential heating between a large body of water and the adjacent land. (Recall that land heats up and cools down more rapidly than a body of water.) A sea breeze usually develops on calm, sunny days when the land is significantly warmer than the adjacent water body, and it alternates with the usually weaker, nighttime land breeze.

A sea breeze begins to form after sunrise as the temperature of the air above the land surface increases while the temperature over the ocean remains largely unchanged. This differential heating between land and water produces a warmer air column over land adjacent to a cooler air column over water. Recall that air pressure drops more rapidly with altitude in a column of cooler (denser) air than in a column of warmer (less dense) air. As a result, the pressure aloft in the warm air column over land is higher than the pressure aloft over the water body—at the same altitude (Figure 7.2A). This pressure difference causes the air aloft to blow away from the land (area of high pressure) toward the water (area of low pressure). The flow aloft is called the *return flow*, even though it generally develops before the sea breeze.

Smartfigure 7.2 **Sea breeze and land breeze**



A. During daylight hours, cooler and denser air over the water moves onto the land, generating a sea breeze.

B. At night the land cools more rapidly than the sea, generating an offshore flow called a land breeze.

Watch **SmartFigure: Local Winds**

> Sea breezes arise because land heats up more rapidly than the adjacent body of water.

The mass transfer of air aloft from land toward the ocean creates a surface high-pressure area over the ocean, where the air collects, and low pressure over land. The *surface* circulation that develops from this redistribution of mass is from the sea toward land, hence the name **sea breeze** (Figure 7.2A). At night, the land cools more rapidly than the sea, and a **land breeze** may develop (Figure 7.2B).

You might have wondered . . .

What is the highest wind speed ever recorded in the United States?

The highest wind speed recorded at a surface station is 372 kilometers (231 miles) per hour, measured April 12, 1934, at Mount Washington, New Hampshire. Wind speed at the observatory atop Mount Washington, 1879 meters (6262 feet) above sea level, averages 56 kilometers (35 miles) per hour. Faster wind speeds have undoubtedly occurred on mountain peaks, but no instruments were in place to record them.

A sea breeze has a significant moderating influence in coastal areas. Shortly after a sea breeze begins, air temperatures over land begin to drop. The cooling effect of these breezes, however, is generally noticeable for only 100 kilometers (60 miles) inland in the tropics, often less than half that distance in the middle latitudes. Relatively cool sea breezes generally begin shortly before noon and reach their greatest intensity—about 10 to 20 kilometers per hour—by midafternoon.

Smaller-scale sea breezes can also develop along the shores of large lakes. Cities near the Great Lakes, such as Chicago, benefit from the "lake breeze" during the summer, when residents typically enjoy cooler temperatures near the lake compared to warmer inland areas. In many places, sea breezes markedly influence the amount of cloud cover and rainfall. The Florida peninsula, for example, experiences increased summer precipitation partly because of convergence associated with sea breezes from both the Atlantic and Gulf coasts (see Figure 4.20). In fact, in midsummer the convective lifting associated with a sea breeze can lead to extensive thunderstorm activity over the Florida peninsula.

Mountain and Valley Breezes

A daily wind similar to land and sea breezes occurs in mountainous regions. During the day, air along mountain slopes is heated more intensely than air at the same elevation over the valley floor (Figure 7.3A). This warmer air glides up the mountain slope and generates a **valley breeze**. Valley breezes can often be identified by the cumulus clouds that develop over adjacent mountain peaks. These breezes may account for late-afternoon thundershowers that occur on warm summer days (Figure 7.4).

Figure 7.3 Valley and mountain breeze

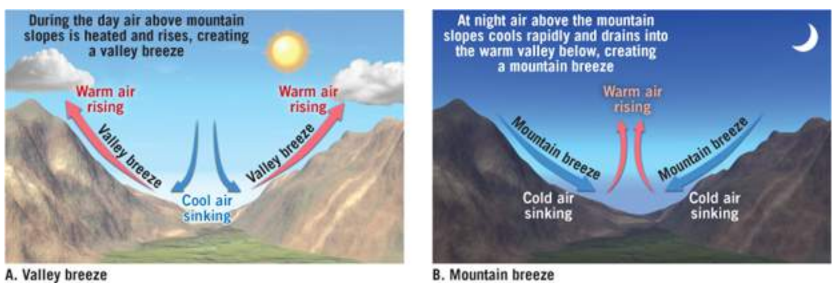


Figure 7.4 Cloud development on mountain peaks signals the occurrence of a daytime upslope (valley) breeze

Sometimes this cloud development can produce a midafternoon thunderstorm.

After sunset, the pattern is reversed. Rapid heat loss along the mountain slopes cools the air, which drains into the valley and causes a **mountain breeze** (Figure 7.3B). Similar cool air drainage can occur in hilly regions with modest slopes. The result is that the coldest pockets of air are usually found in the lowest spots.

Like many other winds, mountain and valley breezes vary by season. Valley breezes are most common during warm seasons, when solar heating is most intense, whereas mountain breezes tend to occur more frequently during cold seasons.

You might have wondered . . .

What is a haboob?

A haboob (from the Arabic word *habb*, meaning “wind”) is a type of local wind that occurs in arid regions. The name was originally applied to strong dust storms in Africa’s Sudan region, where one city experiences an average of 24 haboobs per year. Haboobs generally occur when downdrafts from large thunderstorms reach the surface and swiftly spread out across the desert. Tons of silt, sand, and dust are lifted, forming a whirling wall of debris hundreds of meters high. These dense, dark “clouds” can completely engulf desert towns and deposit enormous quantities of sediment. The deserts of the southwestern United States occasionally experience these dust storms.

Chinook (Foehn) Winds

A **chinook** is a warm, dry wind that flows down the leeward side of mountain slopes in the United States and Canada.* Similar winds in the Alps are called **foehns**. As the air descends the leeward slopes of the mountains, it is heated adiabatically (by compression). Because condensation may have occurred as the air ascended the windward side of the mountain, releasing latent heat, the air descending the leeward side is often much warmer and drier than at a similar elevations on the windward side.

Chinooks are common east of the Colorado Rockies in the winter and spring, when the affected area may be experiencing subfreezing temperatures. Thus, these dry, warm winds often bring drastic change. Within minutes of a chinook's arrival, the temperatures often climb 20°C (36°F), or much more. These winds can rapidly melt snow cover, which explains why they are referred to as "snow-eaters." Chinook winds have been known to melt more than a foot of snow in a single day. A chinook that originated in the Rockies and moved through Loma, Montana, on January 15, 1972, caused the temperature to rise from –54°F to 49°F—an increase of 103°F!

> A chinook is a warm, dry wind that flows down the leeward side of mountain slopes in the United States and Canada.

Chinooks are sometimes viewed as beneficial to ranchers east of the Rockies because they keep the grasslands clear of snow during much of the winter. However, this benefit is offset by the loss of moisture that the snow would add to the soil if it remained until the spring melt.

Another chinook-like wind is the **Santa Ana**. Occurring in southern California, the hot, dry Santa Ana winds greatly increase the threat of fire in this already dry area (Severe & Hazardous Weather 7.2).

Severe & Hazardous Weather 7.2

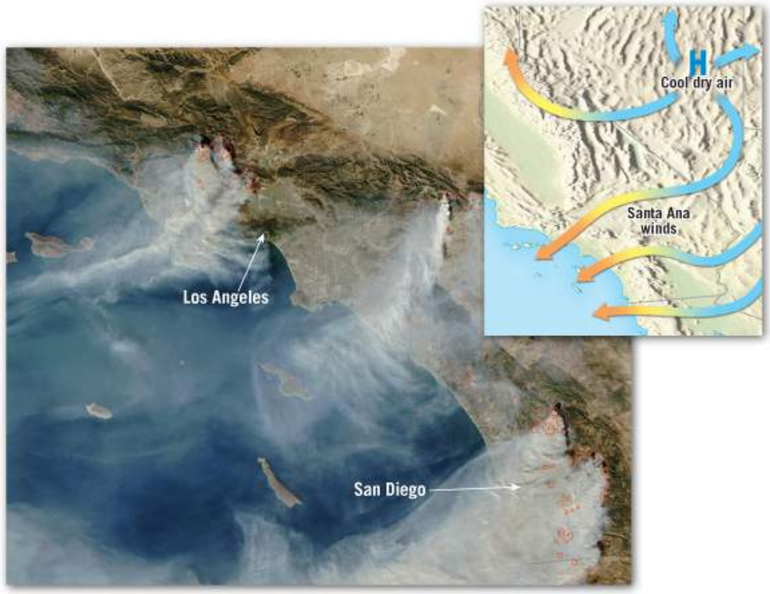
Santa Ana Winds and Wildfires

Santa Ana is the local name for chinook-like winds that characteristically sweep through southern California and northwestern Mexico in the fall and winter. These hot, dry winds are infamous for fanning regional wildfires.

Santa Ana winds are driven by strong high-pressure systems with subsiding air that tend to develop in the fall over the Great Basin. The clockwise flow from the anticyclone directs desert air from Arizona and Nevada westward toward the Pacific (Figure 7.B, **inset**). The wind gains speed as it is funneled down through the canyons of the Coast Ranges, the Santa Ana Canyon in particular—from which the winds derive their name. Adiabatic heating of this already warm, dry air as it descends mountain slopes further accentuates the already parched conditions. Vegetation, seared by the summer heat, is dried even further by these hot winds.

Figure 7.B Wildfires driven by Santa Ana winds

Ten large wildfires rage across southern California in this image taken on October 27, 2003, by NASA's *Aqua* satellite. Inset shows an idealized high-pressure area composed of cool, dry air that drives Santa Ana winds. Adiabatic heating causes the air temperature to increase and the relative humidity to decrease.



Although Santa Ana winds occur every year, they were particularly hazardous in the fall of 2003 and to a lesser extent in 2007, when hundreds of thousands of acres were scorched. In late October 2003, Santa Ana winds began blowing toward the coast of southern California at speeds that sometimes exceeded 100 kilometers (60 miles) per hour. Much of this area is covered by brush known as chaparral and related shrubs. It didn't take much—a careless camper or motorist, a lightning strike, or an arsonist—to ignite fires. Soon a number of small fires occurred in portions of Los Angeles, San Bernardino, Riverside, and San Diego Counties (Figure 7.B). Several quickly developed into wildfires that moved almost as fast as the ferocious Santa Ana winds sweeping through the canyons.

Within a few days, more than 13,000 firefighters were on fire lines extending from north of Los Angeles to the Mexican border. Nearly 2 months later, when all the fires were officially extinguished, more than 742,000 acres had been scorched, over 3000 homes destroyed, and 26 people killed (Figure 7.C). The Federal Emergency Management Agency put the dollar losses at over $2.5 billion. The 2003 southern California wildfires became the worst fire disaster in the state's history.

Figure 7.C Flames from a wildfire move toward a home south of Valley Center, California

Image captured on October 27, 2003.

> Strong Santa Ana winds, coupled with dry summers, have produced wildfires in southern California for millennia.

Strong Santa Ana winds, coupled with dry summers, have produced wildfires in southern California for millennia. These fires are nature's way of burning out chaparral thickets and sage scrub to prepare the land for new growth. When people began building homes and crowding into the fire-prone area between Santa Barbara and San Diego, the otherwise natural problems were compounded. Landscaped properties consisting of highly flammable eucalyptus and pine trees have further increased the hazard risk. In addition, fire prevention efforts have resulted in an unintended consequence: With fewer fires, plant material accumulates to larger-than-normal quantities; so when fires do occur, they are larger and more destructive.

WEATHER SAFETY

Southern California isn't the only place where wind can create dangerous fire hazards. These conditions can occur in any part of the United States. The National Weather Service issues a *Red Flag Warning* when strong winds, low relative humidity, and dry vegetation combine to create conditions in which fires will ignite quickly and grow rapidly. The following safety advice is given for areas under a Red Flag Warning:

- If you see even a small fire, report it immediately.
- Don't light fires, including campfires and barbeque grills.
- Don't park your car on or drive over dry grass.

Apply What You Know

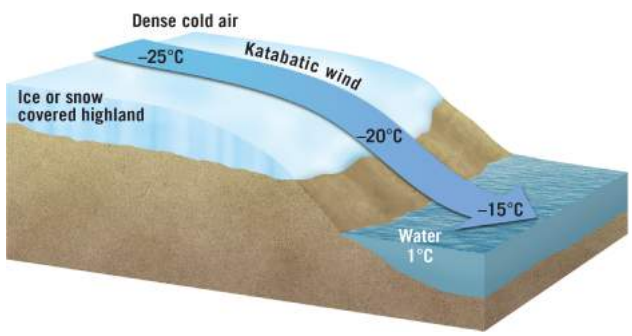
1. Why are Santa Ana winds a threat for coastal areas of southern California?
2. What is a Red Flag Warning, and what are some of the recommended safety precautions?

Katabatic (Fall) Winds

In the winter, areas adjacent to highlands may experience a **katabatic wind**, or **fall wind**. These local winds originate when cold, dense air situated over a highland area, such as the ice sheets of Greenland and Antarctica, begins to move (Figure 7.5). Gravity causes the cold air to cascade over the rim of a highland like a waterfall. Although the air is heated adiabatically, the initial temperatures are so low that the wind arrives in the lowlands still colder and denser than the air it displaces. As this frigid air descends, it occasionally is channeled into narrow valleys, where it acquires velocities capable of significant destruction.

Figure 7.5 Katabatic winds

These winds, also referred to as *fall winds*, travel from ice- or snow-covered highlands, driven mainly by the force of gravity.



A few of the better-known katabatic winds have local names. Most famous is the *mistral*, which blows from the French Alps toward the Mediterranean Sea. Another is the *bora*, which originates in the mountains of the Balkan Peninsula and blows to the Adriatic Sea.

Country Breezes

One mesoscale wind, the **country breeze**, is associated with large urban areas. As the name implies, this circulation pattern is characterized by a light wind blowing into the city from the surrounding countryside. In cities, massive buildings composed of rocklike materials tend to retain the heat accumulated during the day more than the open landscape of outlying areas. The result is that the warm, less dense air over cities rises, which in turn initiates the country-to-city flow. A country breeze is most likely to develop on a relatively clear, calm night. One unfortunate consequence of the country breeze is that pollutants emitted near the urban perimeter tend to drift in and concentrate near the city's center.

Concept Checks 7.2

- In what way are land and sea breezes similar to mountain and valley breezes?
- What are chinook winds? Name two areas where they are common.
- In what way are katabatic (fall) winds different from most other types of local winds?

*The term *chinook* is thought to come from the Native American people who lived in the Pacific Northwest, where the name originated.

7.3 Global Circulation

LO 3   Sketch and describe the three-cell model of global circulation.

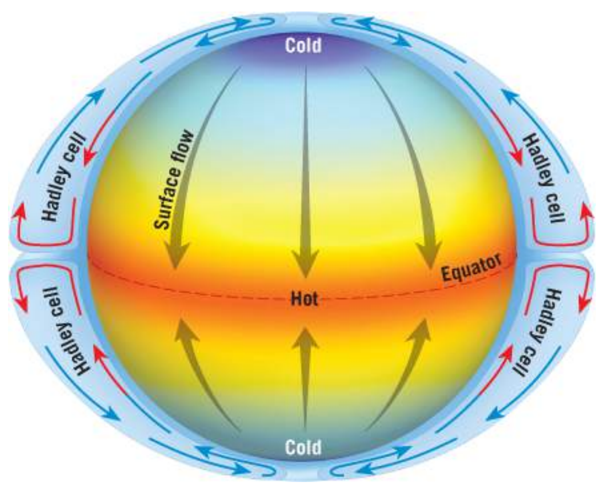
Our knowledge of global winds comes from two sources: the patterns of pressure and winds observed worldwide and theoretical studies of fluid motion. We will first consider the classical model of global circulation that was developed largely from average worldwide temperature distribution. We then modify this idealized model by adding the rotation of Earth to produce more realistic wind patterns using the three-cell circulation model.

Single-Cell Circulation Model

One of the first contributions to the classical model of global circulation came from George Hadley in 1735. Well aware that solar energy drives wind, Hadley proposed that the large temperature contrast between the poles and the equator creates a large *convection cell* in both the Northern and Southern Hemispheres (Figure 7.6).

Figure 7.6 **Global circulation on a nonrotating Earth**

A simple convection system is produced by unequal heating of the atmosphere on a nonrotating Earth.

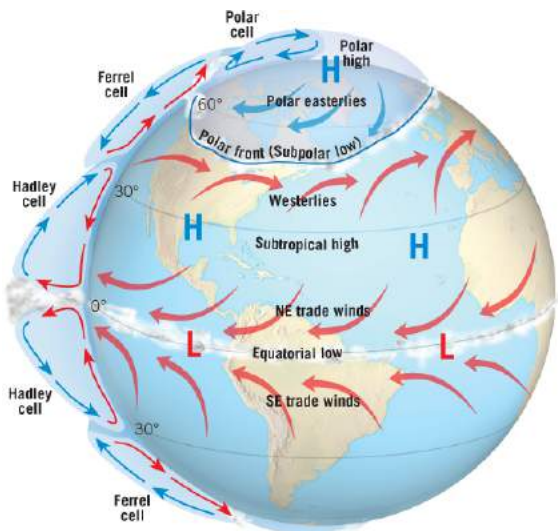


In Hadley's model, warm equatorial air rises until it reaches the tropopause, where it spreads toward the poles. Eventually, this upper-level flow reaches the poles, where cooling causes it to sink and spread out at the surface as equatorward-moving winds. As this cold polar air approaches the equator, it is reheated and rises again. Thus, the circulation proposed by Hadley has upper-level air flowing poleward and surface air moving equatorward. Although correct in principle, Hadley's model does not take into account Earth's rotation.

Three-Cell Circulation Model

In the 1920s, a three-cell circulation model incorporating Earth's rotation was proposed. Although this model has been modified to fit upper-air observations, it remains a useful tool for examining global circulation. Figure 7.7 illustrates the idealized three-cell model and the surface winds that result.

Smartfigure 7.7 Idealized global circulation for the three-cell circulation model on a rotating Earth



Watch **SmartFigure: Global Circulation**

Hadley Cell

In the zones between the equator and roughly 30° latitude north and south, the circulation closely resembles the convection model proposed by Hadley—called the **Hadley cell** in his honor. Near the equator, warm rising air that releases latent heat during the formation of cumulus towers is believed to provide the energy that drives the Hadley cells. As the flow aloft moves poleward, the air begins to subside in a zone between 20° and 35° latitude. Two factors contribute to this general subsidence: (1) As upper-level flow moves away from the stormy equatorial region, radiation cooling becomes the dominant process. As a result, the air cools, becomes denser, and sinks. (2) The Coriolis force becomes stronger with increasing distance from the equator, causing the poleward-moving upper air to be deflected into a nearly west-to-east flow by the time it reaches 30° latitude. This restricts the poleward flow of air. Stated another way, the Coriolis force causes a general pileup of air (convergence) aloft. As a result, general subsidence occurs in the zones between 20° and 35° latitude.

> The three-cell circulation model includes the Hadley cell, the Ferrel cell, and the polar cell.

Eye on the Atmosphere 7.1

This mountain area was cloud free as this summer day began. By afternoon, these clouds had formed.

Apply What You Know

1. With which local wind are the clouds in this photo most likely associated?
2. Describe the process that created the local wind associated with the formation of these clouds.
3. Would you expect clouds such as these to form at night?

This subsiding air between 20° and 35° latitude is relatively dry because it has released its moisture near the equator. In addition, adiabatic heating during descent further reduces the air's relative humidity. Consequently, this subtropical zone of subsidence is the site of many of the world's great deserts, such as the Sahara of North Africa and the Great Australian Desert. Further, surface winds tend to be weak between 20° and 35°

latitude, so this belt was named the **horse latitudes** (see Figure 7.7) because early Spanish sailing ships crossing the Atlantic were sometimes stalled for long periods of time in these waters. If food and water supplies for the horses on board became depleted, the Spanish sailors were forced to throw the horses overboard.

Near the center of the horse latitudes, as the sinking air approaches the surface, it splits into two branches—one flowing poleward and one flowing toward the equator. The equatorward flow is deflected by the Coriolis force to form the reliable **trade winds**, so called because they enabled early sailing ships to move goods between Europe and North America. In the Northern Hemisphere, the trades blow from the northeast, while in the Southern Hemisphere, the trades are from the southeast. The trade winds from both hemispheres meet near the equator, in a region that has a weak pressure gradient. This zone is called the **doldrums**. Here light winds and humid conditions provide the monotonous weather that is the basis for the expression "the doldrums."

Ferrel Cell

In the three-cell model, the circulation between 30° and 60° latitude (north and south), called the **Ferrel cell**, was proposed by William Ferrel to account for the westerly surface winds in the middle latitudes (see Figure 7.7). These **prevailing westerlies** were known to Benjamin Franklin, perhaps the first American weather forecaster, who noted that storms migrated from west to east across the colonies. Franklin also observed that the westerlies were much more sporadic and therefore less reliable than the trade winds for sail power. We now know that it is the migration of cyclones and anticyclones across the midlatitudes that disrupts the general westerly flow at the surface. Because of the significance of the midlatitude circulation in producing our daily weather, we will consider the westerlies in more detail later in this chapter.

Polar Cell

The circulation in a **polar cell** is driven by subsidence near the poles that produces a surface flow that moves equatorward—called the **polar easterlies** in both hemispheres. As these cold polar winds move equatorward, they eventually encounter the warmer westerly flow of the midlatitudes. The region where the flow of cold air clashes with warm air has been named the **polar front**. The significance of this region will be considered later.

> The primary wind zones include the trade winds, which flow toward the equator; the westerlies in the middle latitudes; and polar easterlies, which flow away from the poles.

Concept Checks 7.3

- Briefly describe the idealized global circulation proposed by George Hadley. What are the shortcomings of the Hadley model?
- Name two factors that cause air to subside between 20° and 35° latitude.
- In the idealized three-cell model of atmospheric circulation, most of the United States is situated in which belt of prevailing winds?

7.4 Global Distribution of Pressure and Precipitation

LO 4 Summarize Earth's idealized zonal pressure and precipitation belts. Describe how continents and seasonal temperature changes complicate the idealized pattern.

The idealized three-cell model provides a foundation for Earth's global wind patterns, but actual wind patterns are derived from a more complex distribution of surface air pressure. To simplify our discussion, we will first examine the idealized pressure distribution that would be expected if Earth's surface were uniform—that is, composed entirely of water or smooth land—so that differential heating of land and water is not a complicating factor. We will then turn to real-world pressure systems.

Idealized Zonal Pressure Belts

If Earth's surface were uniform, each hemisphere would have mainly east–west oriented belts of high and low pressure (Figure 7.8). Near the equator, the warm rising branch of the Hadley cells is associated with the low-pressure zone known as the **equatorial low**. This region of ascending moist, hot air is marked by abundant precipitation. Because this region of low pressure is where the trade winds converge, it is also called the **intertropical convergence zone (ITCZ)**. In Figure 7.9, the ITCZ is visible as a band of clouds near the equator.

Figure 7.8 Idealized global distribution of pressure and winds

An imaginary uniform Earth with idealized zonal (continuous) pressure belts.

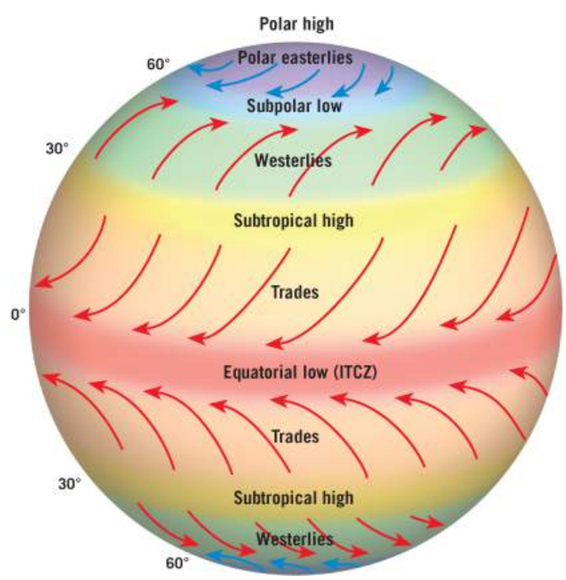


Figure 7.9 The intertropical convergence zone (ITCZ)

This zone of low pressure and convergence is seen as a band of clouds that extends east–west slightly north of the equator.

> Idealized pressure zones include the equatorial low, subtropical highs, subpolar lows, and polar highs.

On either side of the equator at about 20° to 35° latitude, where the westerlies and trade winds originate and go their separate ways, are the high-pressure zones known as the **subtropical highs**. In these zones, a subsiding air column produces weather that is normally warm and dry.

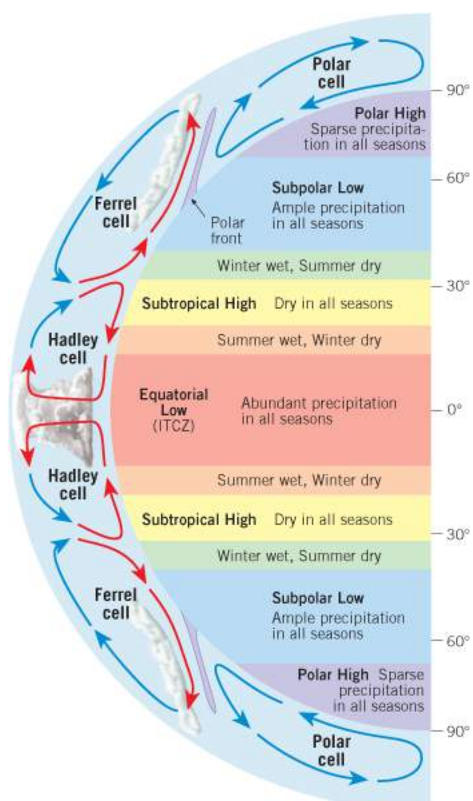
Another low-pressure belt is situated at about 50° to 60° latitude, in a position corresponding to the polar front. Here the polar easterlies and the westerlies clash in the low-pressure convergence zone known as the **subpolar low**. As you will see later, this zone is responsible for much of the stormy weather in the middle latitudes.

Finally, near Earth's poles are the **polar highs**, from which the polar easterlies originate (see Figure 7.8). The polar highs result from surface cooling. Because air near the poles is cold and dense, it exerts higher-than-average surface pressure.

Idealized Precipitation Belts

The precipitation regimes that would be expected from these idealized pressure systems are shown in Figure 7.10. Near the equator, where the trade winds converge, lies the equatorial low (ITCZ), which produces abundant precipitation in all seasons. At about 30° latitude in each hemisphere we find the two subtropical high-pressure belts. In these regions, subsidence contributes to dry conditions throughout the year. Because these pressure systems migrate seasonally with the Sun's vertical rays, the regions between the equatorial low and subtropical highs receive most of their precipitation in the summer, when they are under the influence of the poleward-moving ITCZ. By contrast, in the winter they experience a dry season caused by the subtropical high moving equatorward.

Figure 7.10 Zonal precipitation patterns



> Precipitation roughly follows the zonal pressure pattern of the three-cell model.

The midlatitudes receive most of their precipitation from traveling cyclonic storms. This region is the site of the polar front, the convergence zone between cold polar air and the warmer westerlies. Because the position of the polar front migrates freely between approximately 30° and 70° latitude, most midlatitude areas receive ample precipitation throughout the year.

The polar regions are dominated by high pressure and cold air that holds little moisture. Annually, these regions experience only meager precipitation.

Real-World Pressure Patterns

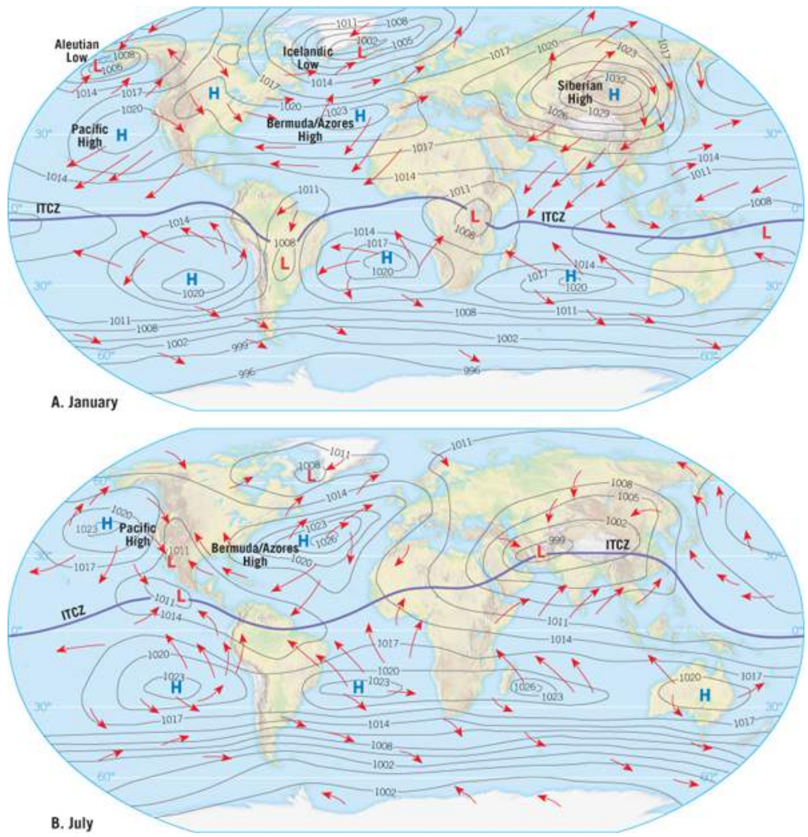
Because Earth's surface is not uniform, the only true zonal distribution of pressure exists along the subpolar low in the Southern Hemisphere, where the ocean is continuous. To a lesser extent, the equatorial low is also continuous. At other latitudes, particularly in the Northern Hemisphere, where there is a higher proportion of land compared to water, the zonal pattern is replaced by semipermanent cells of high and low pressure. They are referred to as *semipermanent* because they move and vary in intensity with the seasons.

> Semipermanent pressure systems are created mainly because Earth's surface is not uniform.

Average global pressure patterns and resulting winds for the months of January and July are shown in Figure 7.11. Notice on these maps that the observed pressure patterns are circular (or elongated) instead of zonal (east–west bands). The most prominent features on both maps are the subtropical highs. These systems are centered between 20° and 35° latitude over the subtropical oceans. When we compare Figure 7.11A (January) with Figure 7.11B (July), we see that some pressure cells are year-round features—the subtropical highs, for example. Others, however, are seasonal. For example, the low-pressure cell over northern Mexico and the southwestern United States is a summer phenomenon and appears only on the July map.

Figure 7.11 **Average surface pressure and associated global circulation**

A. January. **B.** July. Red arrows indicate surface airflow.



January Pressure and Wind Patterns

The **Siberian high**, a very strong high-pressure center positioned over the frozen landscape of northern Asia, is the most prominent feature on the January pressure map (Figure 7.11A). A weaker polar high is located over the chilled North American continent. These cold anticyclones consist of very dense air that accounts for the significant weight of these air columns. Subsidence within these air columns results in clear skies and divergent surface flow.

During the transition from autumn to winter, the Arctic highs strengthen over the continents, while the subtropical highs situated over the oceans become weaker. Further, the average position of the subtropical highs tends to be closer to the eastern margins of the oceans in January than in July. For example, the **Bermuda/Azores high**, which is found near the island of Bermuda in July (Figure 7.11B), migrates eastward toward the Azores, a group of volcanic islands about 1,360 kilometers (850 miles) west of Portugal, in winter (Figure 7.11A).

Also shown on the January map, but absent in July, are two strong semipermanent low-pressure centers. Named the **Aleutian low** and the **Icelandic low**, these cyclonic cells are situated over the North Pacific and North Atlantic, respectively. They are hybrid pressure cells—composites of numerous cyclonic storms that traverse these regions. In other words, so many midlatitude cyclones occur during the winter that these regions almost always experience low pressure. As a result, the areas surrounding the Aleutian and Icelandic lows are frequently cloudy and receive abundant winter precipitation.

> Five strong high-pressure systems exist almost year-round.

July Pressure and Wind Patterns

The pressure pattern over the Northern Hemisphere changes dramatically in summer (see Figure 7.11B). High surface temperatures over the continents generate lows that replace wintertime highs. These thermal lows consist of warm ascending air that triggers inward-directed surface flow and cloudy conditions. The strongest of these low-pressure centers develops over southern Asia, while a weaker thermal low is found in the southwestern United States. The winds resulting from these seasonal pressure patterns over the continents generate *monsoon* winds and precipitation, discussed in more detail later in this chapter.

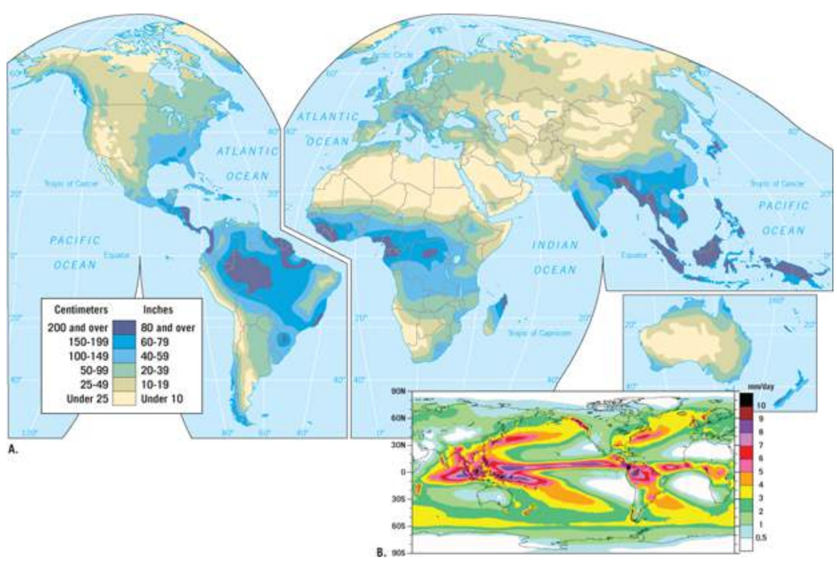
Notice in Figure 7.11B that during the summer months, the subtropical high over the North Atlantic migrates westward and becomes stronger than during the winter months. These strong high-pressure centers dominate the summer circulation over the oceans and pump warm moist air toward the continents that lie to the west. This results in an increase in precipitation over eastern North America.

Global Precipitation Patterns

Figure 7.12 shows the distribution pattern for average annual precipitation around the globe. Although this map may appear complicated, the global winds and pressure systems described above also explain the general precipitation patterns. Drier regions tend to be located near the semipermanent subtropical highs and the polar highs. Wetter regions, by contrast, are found near the semipermanent tropical low (ITCZ) and the subpolar lows. However, if the wind-pressure regimes were the only control of precipitation, the pattern shown in Figure 7.12 would be much simpler.

Figure 7.12 Global distribution of precipitation

A. Average annual precipitation over land. **B.** Annual mean precipitation in millimeters per day for 1979–2010 over the globe.



Watch **Animation: Seasonal Pressure and Precipitation Patterns**

Air temperature is also important in determining precipitation potential. Because cold air has a lower capacity for moisture than warm air, we would expect a latitudinal variation in precipitation, with low latitudes (warm regions) receiving the greatest amounts of precipitation and high latitudes (cold regions) receiving the least.

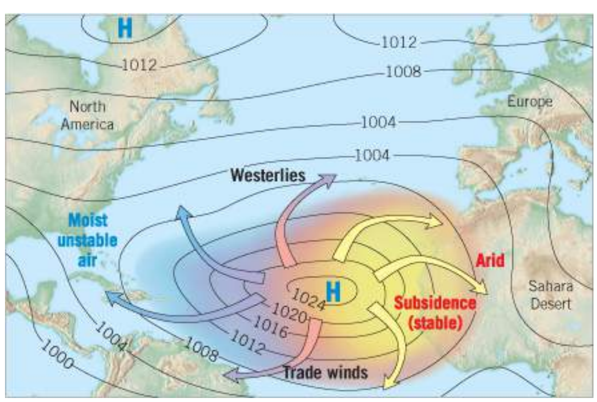
In addition to latitudinal variations in precipitation, the distribution of land and water complicates the precipitation pattern. Large landmasses in the middle latitudes commonly experience decreased precipitation toward their interiors. For example, North Platte, Nebraska, receives less than half the precipitation that falls on the coastal community of Bridgeport, Connecticut, despite being located at the same latitude. Mountain barriers alter precipitation patterns as well. Windward mountain slopes receive abundant precipitation, whereas leeward slopes and adjacent areas are usually deficient in moisture. As a result, arid regions such as the American Southwest are found on the leeward (rain shadow) side of a mountain barrier or in the interior of a continent, cut off from a source of moisture.

> Actual global precipitation patterns are determined mainly by semipermanent pressure systems, the distribution of land and water, air temperatures, and terrain.

The most notable anomaly in the zonal distribution of precipitation occurs in the subtropics, where we find not only many of the world's great deserts but also regions of abundant rainfall (Figure 7.12). This pattern results because the subtropical high-pressure centers that dominate the circulation in these latitudes have different characteristics on their eastern and western sides (Figure 7.13). Subsidence is most pronounced on the eastern side of these high-pressure systems, which results in stable atmospheric conditions. Because these anticyclones tend to crowd the eastern side of an ocean, particularly in the winter, the western portions of the continents adjacent to subtropical highs are arid (Figure 7.13). Centered at approximately 25° north or south latitude east of a subtropical high, we find the Sahara Desert of North Africa, the Namib of southwest Africa, the Atacama of South America, and the deserts of northwestern Mexico and Australia.

Figure 7.13 **Characteristics of subtropical high-pressure systems**

Subsidence on the east side of these systems produces stable conditions and aridity. Surface air that flows out of the western flanks of these highs and traverses large expanses of warm water acquires moisture and may become unstable.



On the western flanks of these highs, however, subsidence is less pronounced. In addition, the surface air that flows out of these highs often traverses large expanses of warm water. As a result, this air acquires moisture through evaporation that acts to enhance its instability. Consequently, landmasses located west of a subtropical high generally receive ample precipitation throughout the year—such as in the southeastern United States (see Figure 7.12).

Monsoons

Large *seasonal* changes in Earth's global circulation are called **monsoons**. Contrary to popular belief, *monsoon* does not mean "rainy season"; rather, it refers to a particular wind system that reverses its direction twice each year. In general, winter is associated with winds that blow predominantly off the continents, called the *winter monsoon*. In contrast, in summer, warm moisture-laden air blows from the sea toward the land. Thus, the *summer monsoon* is usually associated with abundant precipitation over affected land areas.

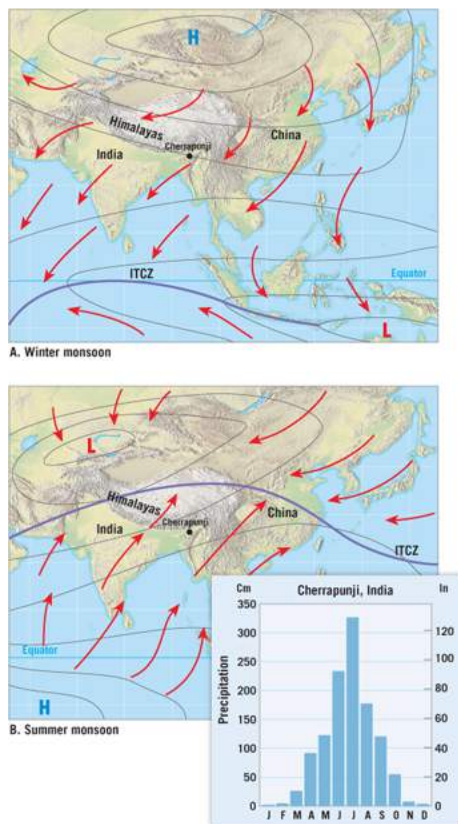
The Asian Monsoon

The best known and best developed monsoon circulation occurs in southeastern Asia—affecting India and surrounding areas as well as parts of China, Korea, and Japan. As with most other winds, the Asian monsoon is driven by pressure differences generated by unequal heating of Earth's surface.

As winter approaches, long nights and low Sun angles result in the accumulation of frigid air over the vast landscape of northern Russia. This generates the cold Siberian high, which ultimately dominates Asia's winter circulation. The subsiding dry air of the Siberian high produces surface flow that moves across southern Asia, producing predominantly offshore winds (Figure 7.14A). By the time this flow reaches India, it has warmed considerably but the air remains extremely dry.

Figure 7.14 Asia’s monsoon circulation

This circulation pattern occurs in conjunction with the seasonal shift of the intertropical convergence zone (ITCZ). **A.** In January, a strong high pressure develops over Asia. The resulting flow of cool air off the continent generates the dry winter monsoon. **B.** With the onset of summer, the ITCZ migrates northward and draws warm, moist air onto the continent.



> Monsoons are large-scale seasonal changes in global circulation that tend to produce wet summers and dry winters.

In contrast, summertime temperatures in the interior of southern Asia often exceed 40°C (104°F). This intense solar heating generates a thermal low over the continent similar to that associated with a sea breeze, but on a much larger scale. The low pressure over southeastern Asia causes moisture-laden air from the Indian and Pacific Oceans to flow over the land, generating cloudy conditions and heavy precipitation typical of summer monsoons.

One of the world's rainiest regions is found on the slopes of the Himalayas, where orographic lifting of incoming moist air from the Indian Ocean produces copious precipitation. Cherrapunji, India, once recorded an annual rainfall of 25 meters (82.5 feet), most of which fell during the 4 months of the summer monsoon (Figure 7.14B).

The Asian monsoon is complex and strongly influenced by the seasonal change in solar heating of the vast Asian continent. In addition, this monsoonal circulation is associated with a large seasonal migration of the ITCZ. With the onset of summer, the ITCZ moves northward over the continent and is accompanied by peak rainfall (Figure 7.14B). The opposite occurs in the Asian winter, as the ITCZ moves south of the equator (Figure 7.14A).

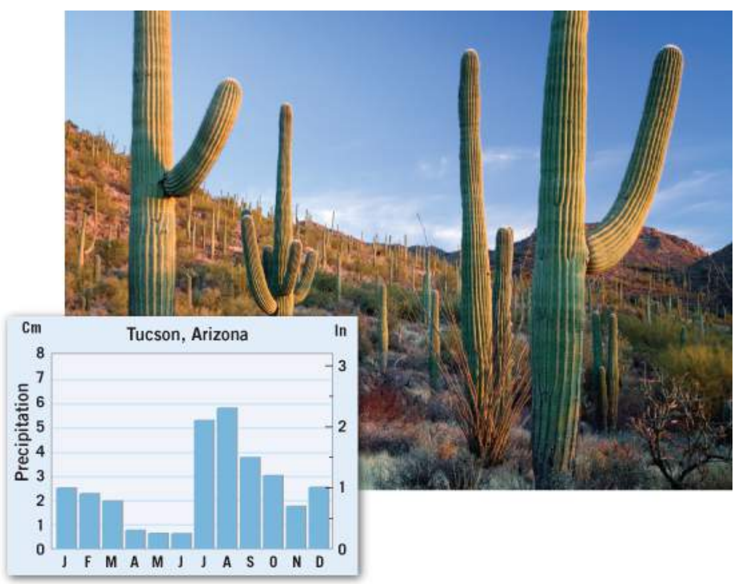
Nearly half the world's population inhabits regions affected by the Asian monsoons. Many of these people depend on subsistence agriculture for their survival. The timely arrival of monsoon rains often means the difference between adequate nutrition and widespread malnutrition.

The North American Monsoon

Other regions, including the American Southwest, experience major seasonal wind shifts. The *North American monsoon* has a circulation pattern that produces a dry spring followed by a relatively rainy summer. This is illustrated by the precipitation pattern observed in Tucson, Arizona, which typically receives nearly 10 times more precipitation in August than in May. As shown in Figure 7.15, summer rains typically last into September before drier conditions are reestablished.

Figure 7.15 The North American monsoon

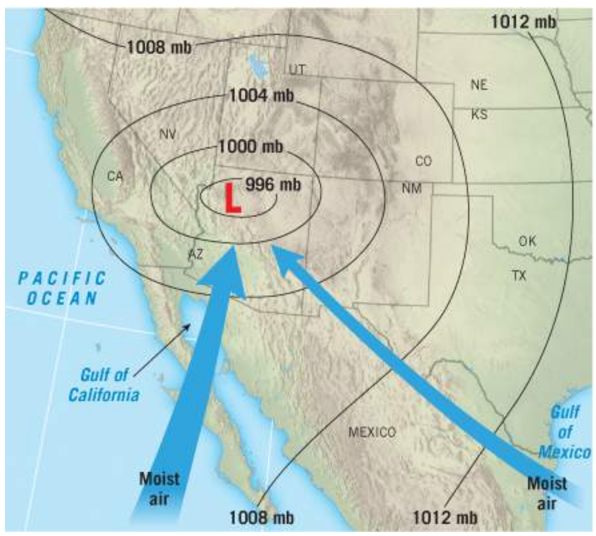
This seasonal circulation is illustrated by the precipitation pattern for Tucson, Arizona.



Summer daytime temperatures in the American Southwest can be extremely high. This intense surface heating generates a thermal low-pressure center over Arizona. The resulting circulation pattern brings warm, moist air from the Gulf of California and, to a lesser extent, from the Gulf of Mexico (Figure 7.16). The supply of atmospheric moisture from nearby marine sources, coupled with the convergence and upward airflow of the thermal low, generates the precipitation this region experiences during the hottest months. Although often associated with the state of Arizona, this monsoon is strongest in northwestern Mexico and is also quite pronounced in New Mexico.

Figure 7.16 Hot summer temperatures over the southwestern United States generate the North American monsoon

High temperatures create a thermal low that draws moist air from the Gulf of California and the Gulf of Mexico. This summer monsoon produces an increase in precipitation, which often comes in the form of thunderstorms, over the southwestern United States and northwestern Mexico.



Concept Checks 7.4

- ■ If Earth had a uniform surface, east–west belts of high and low pressures would exist. Name these zones and the approximate latitude in which each would be found. Which are associated with wet conditions, and which are comparatively dry?
- ■ Describe the seasonal variation in the strength of the Siberian and the Bermuda/Azores highs.
- ■ In addition to global pressure systems, name three factors that influence the global distribution of precipitation.
- ■ Explain the cause of the Asian monsoon. Which season (summer or winter) is the rainy season?

7.5 The Westerlies

LO 5 Explain why the airflow aloft in the middle latitudes has a strong west-to-east component.

Up to this point we have seen that temperature contrasts around the globe result in semipermanent pressure systems, which, in turn, produce surface winds and Earth's precipitation regimes. In addition, the temperature differences between the poles and the equator drive air movements aloft. Most important, the flow aloft that encircles the midlatitudes has a strong influence on our daily weather.

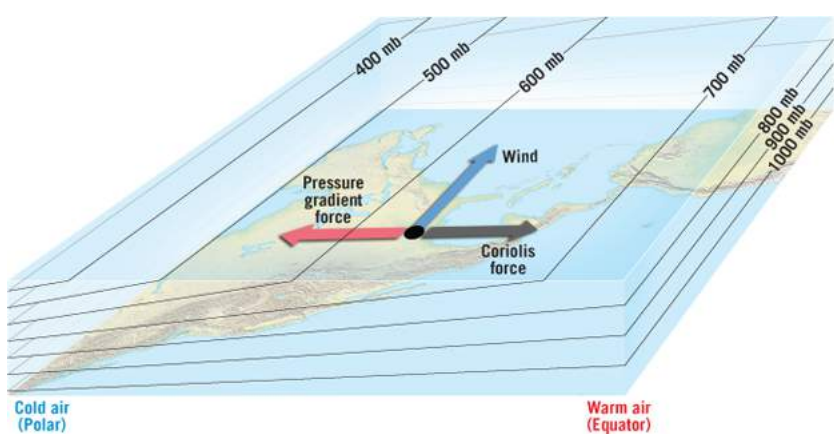
Why Westerlies?

Prior to World War II, upper-air observations were scarce. Since then, aircraft and radiosondes have provided a great deal of data about the upper troposphere. Among the most important discoveries was that airflow aloft in the middle latitudes has a strong west-to-east component, thus the name *westerlies*.

Let us consider the reason for the predominance of westerly flow aloft, which is driven by mainly by the temperature contrast between the poles and equator. Figure 7.17 illustrates the pressure distribution with height over the cold polar region as compared to the much warmer tropics. Recall that because cold air is denser (more compact) than warm air, air pressure decreases more rapidly in a column of cold air than in a column of warm air (see Figure 6.10). The pressure surfaces in Figure 7.17 represent a simplified view of the pressure distribution we would expect to observe from pole to equator.

Figure 7.17 Pressure pattern that produces the westerlies aloft

An idealized pressure gradient develops aloft because of density differences between cold polar air and warm tropical air. Notice that the poleward-directed pressure-gradient force is balanced by an equatorward-directed Coriolis force. The result is a prevailing flow from west to east called the *westerlies*.



Over the equator, where temperatures are higher, air pressure decreases more gradually than over the cold polar regions. Consequently, at the same altitude above Earth's surface, higher pressure exists over the tropics, and lower pressure aloft is the norm above the poles. Thus, the pressure gradient aloft is directed *from the equator* (area of higher pressure) *toward the poles* (area of lower pressure).

> The Coriolis force redirects poleward-moving air to create westerly flow.

When the air aloft begins to advance poleward in response to this pressure gradient force (red arrow in Figure 7.17), the Coriolis force causes a change in the direction of airflow. Recall from Chapter 6 that in the Northern Hemisphere, the Coriolis force causes winds to be deflected to the right. Eventually, a balance is reached between the poleward-directed pressure gradient force and the equatorward-directed Coriolis force to generate *geostrophic* winds, which are winds with a strong west-to-east component. Because the equator-to-pole temperature gradient shown in Figure 7.17 is typical over the globe, a westerly flow aloft should be expected, and it does prevail on most occasions.

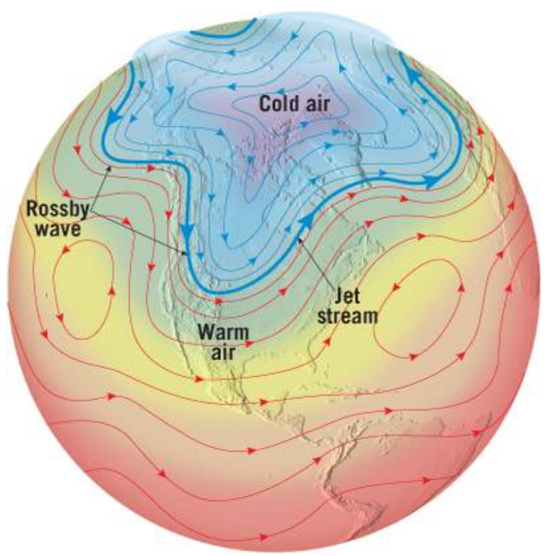
Waves in the Westerlies

As we've seen, in addition to differences in solar heating, air temperatures are the result of the temperature control mechanisms discussed in Chapter 3, especially the distribution of land and water. Because of these temperature differences and other factors, the westerlies aloft do not flow along straight paths, but instead tend to follow wavy or meandering paths that have long wavelengths.

Much of our knowledge of these large-scale motions is attributed to C. G. Rossby, who first explained the nature of these waves. The longest wave patterns, called **Rossby waves**, shown in Figure 7.18, usually consist of four to six meanders that encircle the globe. Although the air flows eastward along this wavy path, these long waves tend to remain stationary or drift slowly from west to east.

Figure 7.18 **Idealized airflow of the westerlies aloft**

The five long-wavelength undulations, called *Rossby waves*, compose this flow. The jet stream is the fast core of this wavy flow.



Watch **Animation: Jet Streams and Rossby Waves**

> Large waves in westerly flow are called Rossby waves.

Rossby waves can have a tremendous impact on our daily weather, especially when they meander widely from north to south. We will consider this role in the following section and again in Chapter 9 as we look at synoptic-scale weather systems.

Concept Checks 7.5

- Why is the flow aloft in the midlatitudes predominantly westerly?
- What are Rossby waves?

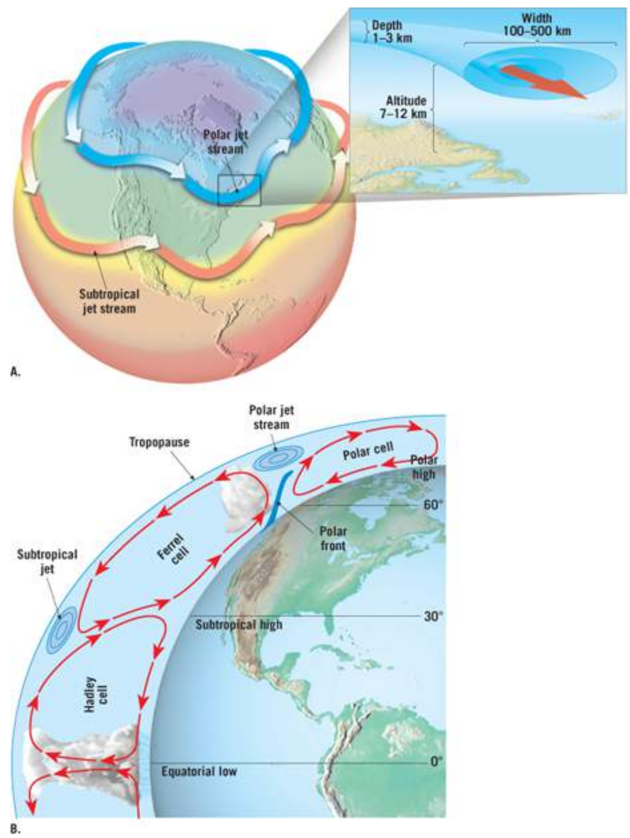
7.6 Jet Streams

LO 6 Explain the origin of the polar jet stream and its relationship to midlatitude cyclonic storms.

Embedded within the westerly flow aloft are narrow ribbons of high-speed winds that typically meander for a few thousand kilometers (Figure 7.19A). These fast streams of air, once considered analogous to jets of water, were named **jet streams**. Jet streams occur near the top of the troposphere and have widths that vary from less than 100 kilometers (60 miles) to over 500 kilometers (300 miles). Wind speeds often exceed 100 kilometers per hour and occasionally approach 400 kilometers (240 miles) per hour.

Figure 7.19 **Jet streams**

A. Approximate positions of the polar and subtropical jet streams. **B.** A cross-sectional view of the polar and subtropical jets in relation to the three-cell model of global circulation.



Although jet streams had been detected earlier, their existence was first dramatically illustrated during World War II. American bombers heading westward toward Japanese-occupied islands sometimes encountered unusually strong headwinds. On abandoning their missions, the planes experienced strong westerly tailwinds on their return flights. Modern commercial aircraft pilots use the strong flow within jet streams to increase their speed when making eastward flights around the globe. On westward flights, of course, they avoid these fast currents of air when possible.

The Polar Jet Stream

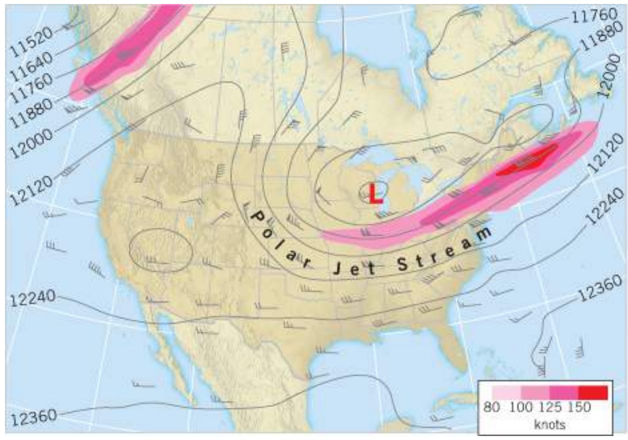
What is the origin of the distinctive energetic winds that exist within the somewhat slower general westerly flow? The key is that large temperature differences at the surface produce steep pressure gradients aloft and hence faster upper-air winds. In winter and early spring, it is not unusual to have a warm balmy day in southern Florida and near-freezing temperatures in Georgia, only a few hundred kilometers to the north. Such large wintertime temperature contrasts lead us to expect faster westerly flow at that time of year. In general, the fastest upper-air winds are located above regions of the globe having large temperature contrasts across very narrow zones.

> The polar jet stream is created by large temperature contrasts at the surface.

These large temperature contrasts occur along narrow, somewhat linear zones called *fronts*. The most prevalent jet stream occurs along a major frontal zone called the *polar front* and is appropriately named the **polar jet stream**, or simply the *polar jet* (Figure 7.19B). In winter the polar jet stream is usually found in the middle latitudes (Figure 7.20). Occasionally, it flows almost due north–south. Sometimes it splits into two jets that may or may not rejoin. Like the polar front, this zone of high-velocity airflow is not continuous around the globe.

Figure 7.20 **Simplified 200-millibar height-contour for January**

The position of the jet stream core (or streak) is shown in dark pink.



On average, the polar jet travels at 125 kilometers (75 miles) per hour in the winter and roughly half that speed in the summer (Figure 7.21). This seasonal difference is due to the much stronger temperature gradient that exists in the middle latitudes during the winter.

Figure 7.21 **The position and speed of the polar jet stream changes with the seasons**

The polar jet stream migrates freely between about 30° and 70° latitude. Shown are flow patterns that are common for summer and winter.

In sync with the zone of maximum solar heating, the jet moves northward during summer and southward in winter. During the coldest winter months, the polar jet stream may extend as far south as Florida (Figure 7.21). With the coming of spring, the zone of maximum solar heating, and therefore the jet, begins a gradual northward migration. By midsummer, its *average* position is near the Canadian border, but it can be located much farther poleward.

The polar jet stream plays a very important role in the weather of the midlatitudes. In addition to supplying energy to help drive storms, it also directs the paths of these storms. Consequently, determining changes in the location and flow pattern of the polar jet is an important part of modern weather forecasting. As the polar jet shifts northward, there is a corresponding northward shift in outbreaks of severe thunderstorms and tornadoes. In February, most thunderstorms and tornadoes occur in the states bordering the Gulf of Mexico, but by late spring the center of this activity moves to the Northern Plains and Great Lakes states.

The location of the polar jet stream also affects other surface conditions, particularly temperature and humidity. When it is situated substantially equatorward of your location, the weather will be colder and drier than normal. Conversely, when the polar jet moves poleward of your location, warmer and more humid conditions will prevail.

Subtropical Jet Stream

A semipermanent jet, called the **subtropical jet stream**, is located about 30° latitude in both hemispheres (see Figure 7.19). At an altitude of about 13 kilometers (8 miles), the subtropical jet stream is mainly a wintertime phenomenon. Somewhat slower than the polar jet, this west-to-east current is centered on the poleward side of the Hadley cells (see Figure 7.19B).

The subtropical jet is often characterized by a band of middle to high clouds that doesn't usually result in stormy weather (Figure 7.22). However, the subtropical jet can contribute to major winter snowstorms over the midlatitudes in the Northern Hemisphere, when it interacts with the polar jet. In addition, when the subtropical jet sweeps northward in the winter, it may bring warm, humid conditions to the Gulf states, particularly southern Florida.

Figure 7.22 Infrared image of the subtropical jet stream

In this image, the subtropical jet appears as a band of cloudiness extending from Mexico to Florida.

Unlike the polar jet, which is generated by marked temperature differences found at higher latitudes, there is no strong temperature contrast in the subtropics. Instead, the subtropical jet is mainly a consequence of Earth's rotation—primarily the fact that Earth (and the atmosphere) rotates faster at the equator than places at higher latitudes. Imagine a parcel of air starting at rest (relative to Earth's surface) high over the equator. As the air moves poleward as part of the upper Hadley circulation, it conserves its rotational velocity, called *angular momentum*, such that it moves faster than Earth's surface. As a result, the subtropical jet is created as air aloft moves toward the poles, and the Coriolis force turns these accelerating winds to the right until finally, at about 30° latitude, they are moving eastward. The resulting fast-moving stream of air, traveling from west to east, is known as the subpolar jet stream.

> The subtropical jet stream is a wintertime jet that is weaker than the polar jet stream.

Jet Streams and Earth's Heat Budget

In Chapter 2 we introduced wind's role in maintaining Earth's heat budget by transporting heat from the equator toward the poles. But how exactly does this happen? Although the flow in the tropics (Hadley cell) is somewhat *meridional* (north–south), at most other latitudes the flow is *zonal* (west–east). The reason for the zonal flow, as we have seen, is the Coriolis force. The question we now consider is: *How can wind with a west-to-east flow transfer heat from south to north?*

> The important function of heat transfer is accomplished by the wavy flow (Rossby waves) of the westerlies centered on the polar jet stream.

You might have wondered . . .

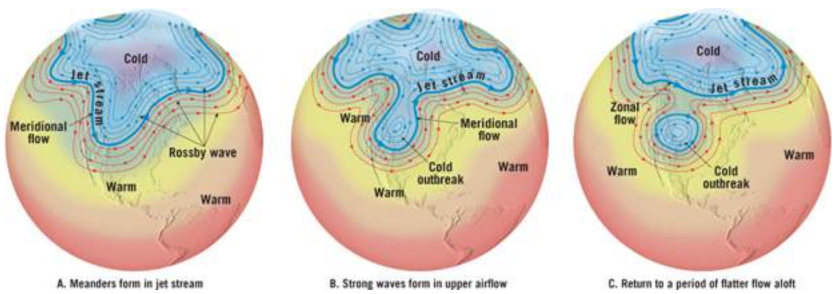
Why do pilots of commercial aircraft always remind passengers to keep their seat belts fastened, even in ideal flying conditions?

The reason for this request is *clear air turbulence*, a phenomenon that occurs when airflow in two adjacent layers moves at different velocities. This can happen when the air at one level travels in a different direction from the air above or below it. More often, however, it occurs when air at one level travels faster than air in an adjacent layer. Such movements create eddies (turbulence) that can cause the plane to move suddenly up or down.

There may be periods of a week or more when the flow in the polar jet is essentially west to east. When this condition prevails, relatively mild temperatures occur south of the jet stream, and cooler temperatures prevail to the north. Then, with minimal warning, the flow aloft may begin to meander and produce large-amplitude waves that exhibit a more pronounced north-to-south flow, as shown in Figure 7.23A and Figure 7.23B. Such a change causes cold air to advance equatorward and warm air to flow poleward. In addition, a cold air mass may become detached and produce very cold conditions and strong storms along its margins (Figure 7.23C).

Figure 7.23 Cyclic changes occur in the upper-level airflow of the westerlies

The flow, which has the jet stream as its axis, starts out nearly straight and then develops meanders and cyclonic activity that dominate the weather.



This redistribution of energy eventually results in a weakened temperature gradient and a return to a more zonal flow aloft (Figure 7.23C). Therefore, the wavy flow of the westerlies centered on the polar jet plays an important role in Earth's heat budget.

Concept Checks 7.6

- How is the polar jet stream generated?
- At what time of year should we expect the fastest polar jet streams? Explain.
- Explain how the wavy flow centered on the jet stream helps balance Earth's heat budget.

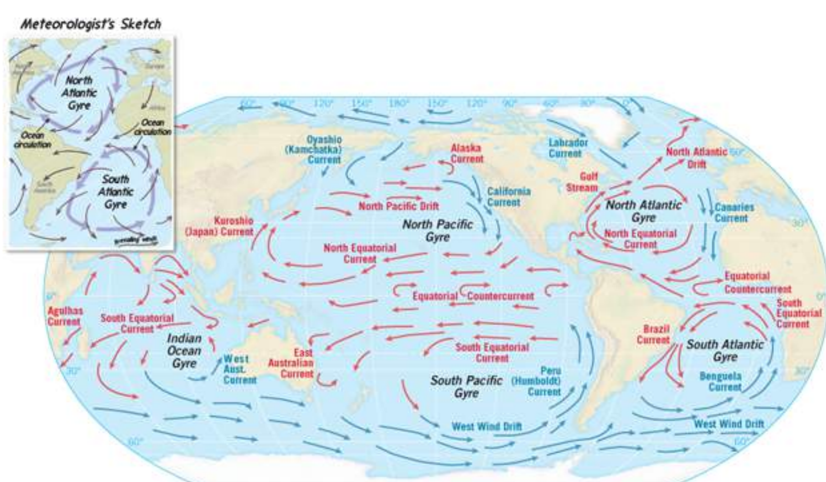
7.7 Global Winds and Ocean Currents

LO 7 Sketch and label the major ocean currents on a world map.

Energy is passed from moving air to the surface of the ocean through friction—winds blowing steadily across the ocean drag the water along with them. Because winds are the primary driving force of surface-ocean currents, a relationship exists between atmospheric circulation and oceanic circulation, as illustrated by a comparison of Figure 7.24 and Figure 7.11. Oceanic circulation in turn can influence weather at scales from local to global, a topic covered in more detail in Section 7.8.

Smartfigure 7.24 Major surface-ocean currents

The ocean's surface circulation is organized into five major gyres. Poleward-moving currents are warm, and equatorward-moving currents are cold. Ocean currents play an important role in redistributing heat around the globe. In the smaller inset map, broad arrows show the idealized surface circulation for the Atlantic, and the thin arrows show prevailing winds. Winds provide the energy that drives the ocean's surface circulation.



Watch **SmartFigure: Gyres**

Watch **Animation: Ocean Currents**

Subtropical Highs and Ocean Gyres

As shown in Figure 7.24, positioned north and south of the equator are two westward-moving currents, the North and South Equatorial Currents. These currents derive their energy principally from the trade winds that blow from the northeast and southeast, respectively, toward the equator. The Coriolis force deflects surface currents poleward to form clockwise spirals in the Northern Hemisphere and counterclockwise spirals in the Southern Hemisphere. These nearly circular ocean currents, called **gyres**, are centered under the five major subtropical high-pressure systems—located in both the southern and northern Atlantic and Pacific Oceans and in the Indian Ocean (Figure 7.24).

> Ocean gyres are centered under and generated by the winds associated with the five major subtropical high-pressure systems.

In the North Atlantic, the equatorial current is deflected northward through the Caribbean, where it becomes the *Gulf Stream*. As the Gulf Stream moves along the eastern coast of the United States, it is strengthened by the prevailing westerly winds. As it continues northeastward beyond the Grand Banks, it gradually widens and slows until it becomes a vast, slowly moving current known as the North Atlantic Drift. The North Atlantic Drift splits as it approaches Western Europe. Part moves northward past Great Britain toward Norway, while the other portion is deflected southward as the cool Canary Current. As the Canary Current moves south, it eventually merges with the North Equatorial Current.

The North Atlantic Drift, an extension of the warm Gulf Stream, keeps wintertime temperatures in Great Britain and much of Western Europe warmer than would be expected for their latitudes. This moderating effect can get blown far inland by the diverging winds associated with the Bermuda/Azores subtropical high.

Cold currents, by contrast, exert their greatest influence in the tropics and middle latitudes along western coastlines. This cooling influence is also blown inland by diverging winds around subtropical highs. For example, the Pacific High blows air moderated by the California Current inland to keep coastal California temperatures moderate year-round.

Ocean Currents and Upwelling

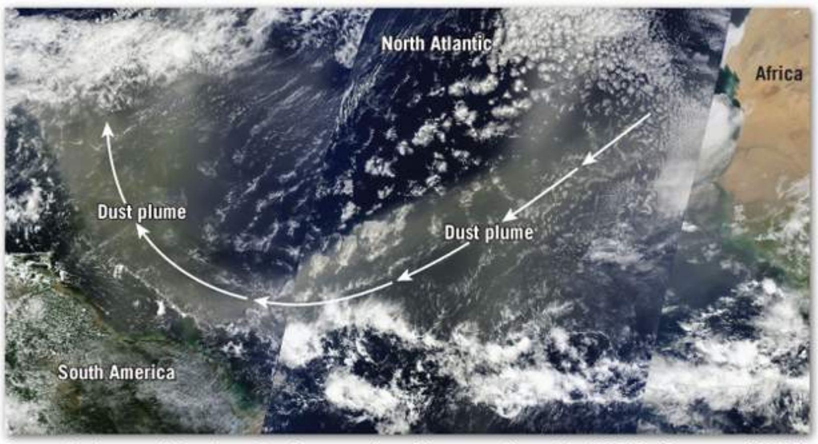
Upwelling, the rising of cold water from deeper layers to replace warmer surface water, is a common wind-induced vertical movement. It is most characteristic along the eastern shores of the global oceans, most notably along the coasts of California, Peru, and West Africa. As the currents in these locations move equatorward, the Coriolis force causes the surface water to turn away from the shore. As the surface layer moves away from the coast, it is replaced by nutrient-filled water that "upwells" from below the surface. This slow upward flow from depths of 50 to 300 meters (165 to 1000 feet) brings water that is cooler than the water it replaces and creates a characteristic coastal zone of relatively cool water favorable to plant growth and marine life.

> Upwelling occurs in areas where winds blow parallel to the coast toward the equator.

Swimmers accustomed to the waters along the mid-Atlantic states of the United States might find a dip in the Pacific on central California's coast a chilling surprise. In August, when water temperatures along the Atlantic shore usually exceed 21°C (70°F), the surf along the coast of California is only about 15°C (60°F).

Eye on the Atmosphere 7.2

This image shows a January dust storm in Africa that produced a dust plume reaching all the way to the northeast coast of South America. Plumes such as this transport an estimated 40 million tons of dust from the Sahara Desert to the Amazon basin each year. The minerals carried by these dust plumes help to replenish nutrients that are continually being washed out of rain forest soils by heavy tropical rains.



Composite image stitched together from a series of images collected by MODIS. (Courtesy of NASA)

Apply What You Know

1. Notice that the dust plume follows a curved path. Does the atmospheric circulation carrying this dust plume exhibit a clockwise or a counterclockwise rotation?
2. What global pressure system was responsible for transporting this dust from Africa to South America?

Concept Checks 7.7

■ What is the primary driving force of surface-ocean currents?

■ Name the five subtropical gyres.

■ Describe the process of upwelling. Why is an abundance of marine life associated with these areas?

7.8 El Niño, La Niña, and the Southern Oscillation

LO 8 Describe the Southern Oscillation and its relationship to El Niño and La Niña. List climate impacts of El Niño and La Niña.

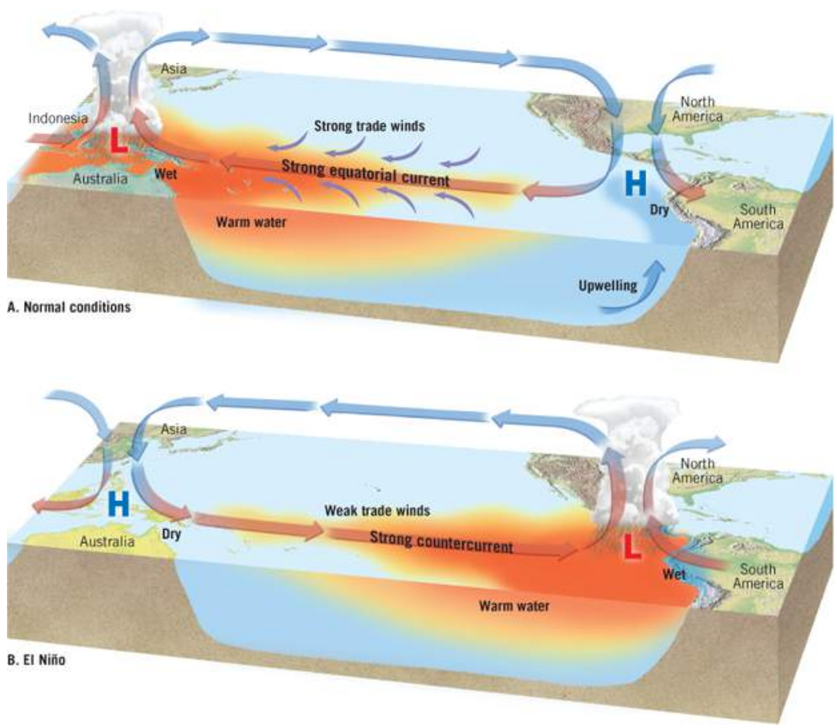
Fishermen from Ecuador and Peru were the first to recognize a gradual warming of waters in the eastern Pacific in December or January in certain years. Because the warming usually occurred near the Christmas season, the event was named **El Niño**—“little boy,” or “Christ child,” in Spanish. These periods of abnormal sea-surface warming occur at irregular intervals of 2 to 7 years and usually persist for spans of 9 months to 2 years. Today, El Niño is noted for its potentially catastrophic impact on the weather and economies of Peru, Chile, Indonesia, and Australia, among other countries.

Normal versus El Niño Conditions

During normal conditions, there is a high pressure off the coast of equatorial South America west of Ecuador, as shown in Figure 7.25A. This high is associated with sinking air and dry conditions, as well as upwelling of nutrient-rich water along the west coast of South America. Strong trade winds blow westward from this equatorial high-pressure zone toward an area of low pressure located in the western Pacific near Indonesia, directly north of Australia. This low-pressure area is associated with rising air and wet conditions, as shown in Figure 7.25A.

Figure 7.25 The relationship between normal conditions and El Niño

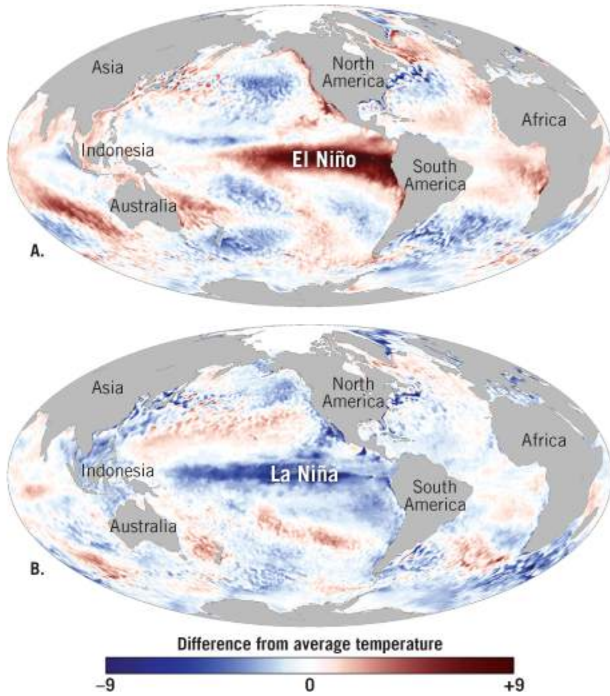
A. During normal conditions, strong trade winds drive the equatorial currents toward the west. At the same time, the strong Peru Current causes upwelling of cold water along the west coast of South America. **B.** During an El Niño event, the pressure over the eastern Pacific drops, while the pressure over the western Pacific rises. This causes the trade winds to diminish, leading to an eastward movement of warm water along the equator. This strengthens the equatorial countercurrent, causing surface waters of the central and eastern Pacific to warm, with far-reaching consequences for weather patterns.



Watch Video: El Niño

With the approach of El Niño, the high pressure off the coast of South America weakens (Figure 7.25B). This reduces the strength of the trade winds and creates a strong equatorial countercurrent, which amasses large quantities of *warmer-than-normal* water along the west coast of South America (Figure 7.26A). This unusually warm water and associated low pressure in the equatorial Pacific causes normally arid areas of Ecuador, Peru, and Chile to receive above-average rainfall. The result can be major flooding in the affected areas. In addition, the warm surface water blocks the upwelling of colder, nutrient-filled water—the primary food source for millions of small feeder fish (mainly anchovies)—that typically rises from below. Indonesia and other areas in the western Pacific, however, tend to be much drier than usual and may experience drought and wildfires.

Figure 7.26 **Sea-surface temperature anomaly associated with El Niño and La Niña**



Watch **Video: La Niña**

> El Niño events bring warmer-than-normal sea-surface temperatures to the equatorial Pacific off the west coast of South America. These tend to be associated with wet conditions in coastal South America and drier-than-normal conditions in Indonesia.

The circulation associated with El Niño eventually returns to normal conditions or is replaced by a La Niña event. **La Niña**, which means "little girl," is essentially a *strengthening* of normal conditions and the opposite of El Niño. A La Niña event is associated with *colder-than-normal sea-surface temperatures* in the central and eastern equatorial Pacific (Figure 7.26B). In addition, the atmospheric circulation in the equatorial Pacific during La Niña is dominated by stronger-than-average trade winds. These wind systems, in turn, generate a strong equatorial current that flows westward away from South America toward Indonesia and Australia. This circulation pattern and associated low pressure in the western Pacific can result in flooding in northeastern Australia and Indonesia, whereas drier-than-normal conditions occur along the coastal areas of western South America.

> La Niña is a strengthening of normal conditions and the opposite of El Niño—resulting in drier-than-normal conditions in western South America and flooding in northeastern Australia and Indonesia.

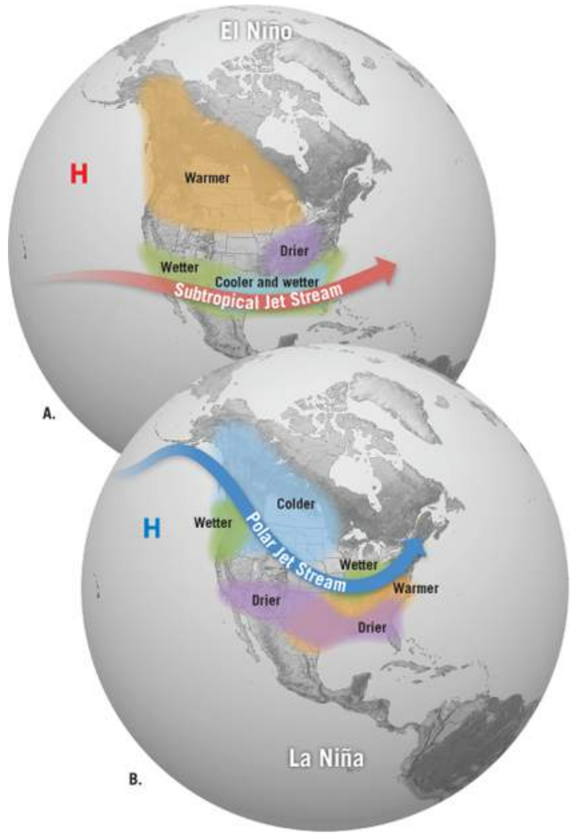
In addition, during La Niña the cold ocean current that flows equatorward along the coast of Chile and Peru intensifies. This surface current, called the Peru Current, encourages upwelling. Thus, La Niña has become known as the "gift giver" because the nutrients carried upward are a boon to marine life, making fishing particularly good during these periods of strong upwelling.

Global Impact of El Niño

The climatic fluctuations associated with El Niño and La Niña have been known for years but were considered a local phenomenon. Meteorologists now recognize that El Niño and La Niña are part of the global atmospheric circulation pattern that affects the weather at great distances from the equatorial regions of the Pacific. Although the effects of these circulation patterns are not always predictable, some locales appear to be affected more consistently than others.

The most obvious impacts of El Niño are flooding along the west coast of South America and drought in Indonesia and Australia. Beyond the equatorial Pacific, winter temperatures are warmer than normal in the north-central United States and parts of Canada (Figure 7.27A). In addition, significantly wetter winters are experienced in the southwestern United States and northwestern Mexico, while the southeastern United States experiences wetter and cooler conditions. One major benefit of El Niño is a lower-than-average number of Atlantic hurricanes.

Figure 7.27 **Impacts of El Niño and La Niña across North America**



The El Niño of 2015–2016 was particularly strong. Impacts included mudslides in California, heavy snows in Arizona, and flooding in Missouri. California's drought was quickly replaced by widespread flooding and coastal erosion. The Midwest, however, enjoyed a warmer-than-normal winter. Outside the United States, Ethiopia experienced drought, while flooding occurred along western South America, and widespread fires devastated parts of Indonesia (Figure 7.28).

Figure 7.28 Fires in Indonesia during a strong El Niño in September 2015

Fires were particularly severe in southern Sumatra and Borneo because of lack of rainfall and intentional lighting of fires by farmers to manage crops. Northern Indonesia was not affected.

Global Impact of La Niña

La Niña was once thought to be the normal conditions that occur between two El Niño events, but meteorologists now consider La Niña an important atmospheric phenomenon in its own right. Researchers have come to recognize that colder-than-average surface temperatures in the central and eastern equatorial Pacific can trigger a La Niña event that exhibits a distinctive set of weather patterns.

Typical La Niña winter weather includes cooler and wetter conditions over the northwestern United States and especially cold winter temperatures in the Northern Plains states, while unusually warm conditions occur in the Southwest and Southeast (Figure 7.27B). In the western Pacific, La Niña events are associated with wetter-than-normal conditions. The 2010–2011 La Niña contributed to a deluge in Australia, resulting in one of the country's worst natural disasters: Large portions of the state of Queensland were extensively flooded. Another La Niña impact is more frequent hurricane activity in the Atlantic. A recent study concluded that the cost of hurricane damages in the United States is 20 times greater in La Niña years than in El Niño years.

Southern Oscillation

El Niño and La Niña events are strongly related to changes in the global pressure patterns. Each time an El Niño occurs, the atmospheric pressure drops over large portions of the eastern Pacific and rises in the tropical portions of the western Pacific (see Figure 7.25A). Then, as a major El Niño event comes to an end, the pressure difference between these two regions swings back in the opposite direction, triggering a La Niña event (see Figure 7.25B) or moving back to normal conditions.

> Oscillation of pressure systems in the equatorial Pacific Ocean leads to the formation of El Niño and La Niña.

This seesaw pattern of atmospheric pressure between the eastern and western Pacific is called the **Southern Oscillation**. Together, El Niño and the Southern Oscillation are called ENSO. Low pressure in the western Pacific strengthens the trade winds, which move warm, tropical water toward Australia and Indonesia. By contrast, a decrease in pressure in the eastern Pacific weakens the trade winds and strengthens the equatorial countercurrents, which amass large quantities of warm water along the coasts of Peru and Chile. The changes in atmospheric pressure create the wind patterns that produce the weather associated with El Niño and La Niña events.

The link between the weather occurring in widely separated regions of the globe is called a **teleconnection**. The sea-surface temperature anomaly associated with an El Niño event, where warming of the eastern Pacific is associated with winter flooding in southern California, is an example. In addition, there appears to be a teleconnection between a strong El Niño and a weak Asian monsoon.

Because sea-surface temperatures are often predictable months in advance, understanding teleconnection patterns allows meteorologists to make climatic predictions for distant locations (Figure 7.29A, B). For instance, predicting the start of an El Niño enables meteorologists to predict North American precipitation and temperature patterns weeks or months in advance. National Weather Service predictions for periods from 1 to 13 months into the future are called *climate outlooks*.

Figure 7.29 Climatic impacts of El Niño and La Niña around the globe in winter

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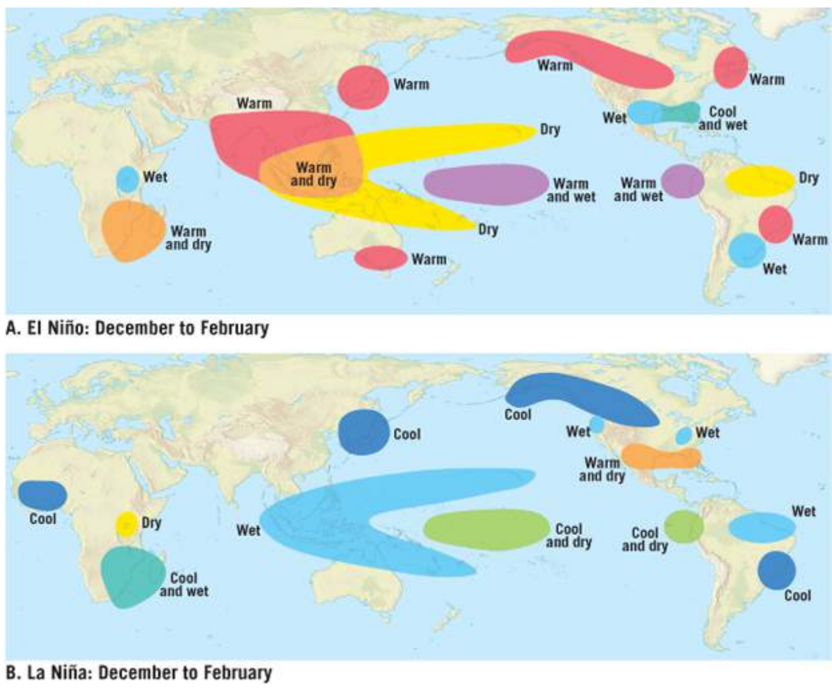
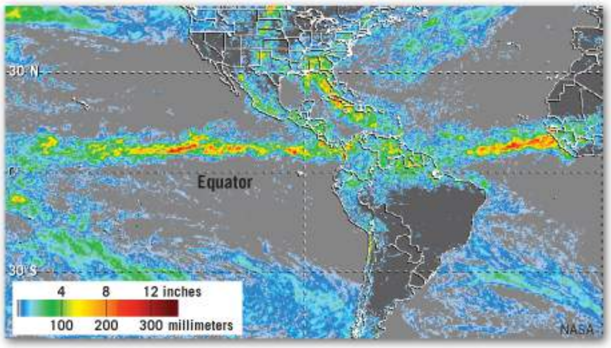


Watch **Animation: El Niño and La Niña**

Eye on the Atmosphere 7.3

This satellite image was produced with data from the *Tropical Rainfall Measuring Mission (TRMM)*. Notice the band of heavy rainfall shown in reds and yellows that extends east–west across the image.



Apply What You Know

1. With which pressure zone is this band of rainy weather associated?
2. Is it more likely that this image was acquired in July or January? Explain.

Concept Checks 7.8

- Describe how a major El Niño event tends to affect the weather in Peru and Chile as compared to Indonesia and Australia. Why does it affect the weather in this way?
- Briefly describe the Southern Oscillation and how it is related to El Niño and La Niña.
- Describe how an El Niño event might affect the climate in North America during the winter. Describe the same for a La Niña event.

Concepts in Review

7.1 Scales of Atmospheric Motion

LO 1 Distinguish microscale, mesoscale, and macroscale winds, and give an example of each.

Key Terms

microscale wind

mesoscale wind

macroscale wind

planetary-scale wind

synoptic-scale wind

- The smallest scale of air motion is the microscale, which includes gusts and dust devils that normally last for seconds or, at most, minutes.
- Mesoscale winds, such as thunderstorms, tornadoes, and land and sea breezes, are usually less than 100 kilometers (60 miles) across and often last minutes to hours.
- The largest wind patterns, called macroscale winds, are divided into two categories: planetary scale and synoptic scale. Planetary-scale winds are exemplified by the westerlies and trade winds that last for weeks or more. Synoptic-scale winds, such as midlatitude cyclones and anticyclones, are easily identified on weather maps and last days to a week.

Macroscale winds NASA

7.2 Local Winds

LO 2 List five types of local winds and describe their formation.

Key Terms

sea breeze

land breeze

valley breeze

mountain breeze

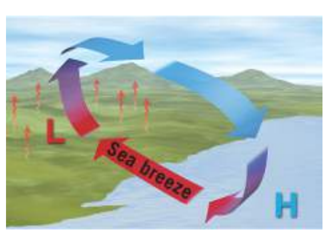
chinook (foehn)

Santa Ana

katabatic wind (fall wind)

country breeze

- Most winds are caused by pressure differences that arise because of temperature differences due to unequal heating of Earth's surface. Most local winds are linked to temperature and pressure differences that result from variations in topography or in local surface conditions.
- Sea and land breezes form along coasts and are brought about by temperature contrasts between land and water. Valley and mountain breezes occur in mountainous areas, where the air along slopes heats differently from the air at the same elevation over the valley floor. Chinook and Santa Ana winds are warm, dry winds created when air descends the leeward side of a mountain and warms by compression.



7.3 Global Circulation

LO 3 Sketch and describe the three-cell model of global circulation.

Key Terms

Hadley cell

horse latitudes

trade winds

doldrums

Ferrel cell

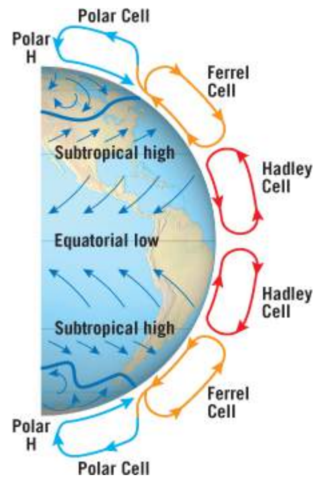
prevailing westerlies

polar cell

polar easterlies

polar front

- The three-cell circulation model for each hemisphere provides a simplified view of global circulation. According to this model, atmospheric circulation cells are located between the equator and 30° latitude, 30° and 60° latitude, and 60° latitude and the poles.
- Trade winds exist between the equator and 30°. The circulation between 30° and 60° latitude (north and south) results in the prevailing westerlies.
- Air that moves equatorward from the poles produces the polar easterlies in both hemispheres.



Polar Cell
Polar H
Ferrel Cell
Subtropical high
Hadley Cell
Equatorial low
Hadley Cell
Subtropical high
Ferrel Cell
Polar H
Polar Cell

7.4 Global Distribution of Pressure and Precipitation

LO 4 Summarize Earth's idealized zonal pressure and precipitation belts. Describe how continents and seasonal temperature changes complicate the idealized pattern.

Key Terms

equatorial low

intertropical convergence zone (ITCZ)

subtropical high

subpolar low

polar high

Siberian high

Bermuda/Azores high

Aleutian low

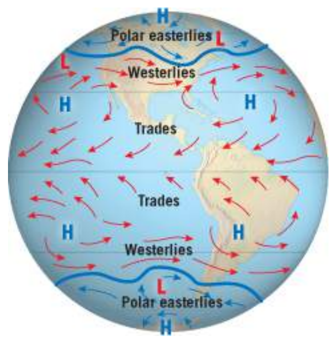
Icelandic low

monsoon

- If Earth's surface were uniform, four latitudinally oriented belts of pressure would exist in each hemisphere—two high and two low. Beginning at the equator, the four belts would be the (1) equatorial low, also referred to as the intertropical convergence zone (ITCZ); (2) subtropical high, at about 20° to 35° on either side of the equator; (3) subpolar low, situated at about 50° to 60° latitude; and (4) polar high, near Earth's poles.
- The general features of the global distribution of precipitation can be explained by global winds and pressure systems. In general, regions influenced by high pressure experience dry conditions. Regions under the influence of low pressure receive ample precipitation.
- Because Earth's surface is not uniform, the zonal pattern is replaced by semipermanent cells of high and low pressure. These cells in turn

influence global precipitation patterns.

- In addition to pressure, influences on the global distribution of precipitation include air temperature, the distribution of continents and oceans, and terrain.
- Monsoons are wind systems that exhibit a pronounced seasonal reversal in direction, such as the Asian monsoon and the much smaller North American monsoon.



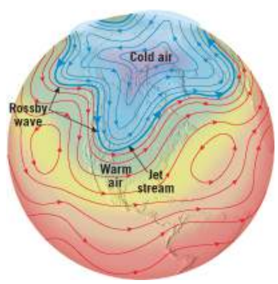
7.5 The Westerlies

LO 5 Explain why the airflow aloft in the middle latitudes has a strong west-to-east component.

Key Term

Rossby wave

- The airflow aloft in the middle latitudes is predominately from west to east, called the westerlies. The westerlies are driven by the pressure gradient aloft caused by the temperature contrast between the poles and equator.
- The westerlies follow wavy paths that have long wavelengths, called Rossby waves, which usually consist of four to six meanders that encircle the globe.



7.6 Jet Streams

LO 6 Explain the origin of the polar jet stream and its relationship to midlatitude cyclonic storms.

Key Terms

jet stream

polar jet stream

subtropical jet stream

- Embedded within the westerly flow aloft are narrow ribbons of high-speed winds, called jet streams, that meander for thousands of kilometers. Polar jet streams result from large temperature contrasts at Earth's surface.

NASA

7.7 Global Winds and Ocean Currents

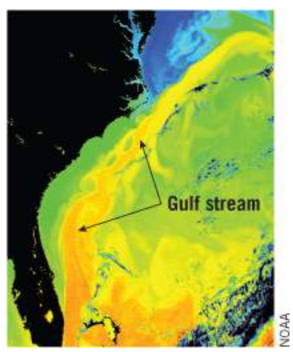
LO 7 Sketch and label the major ocean currents on a world map.

Key Terms

gyre

upwelling

- The global wind system is the primary driving force of ocean currents. These nearly circular ocean currents, called gyres, are centered under the five major subtropical high-pressure systems.
- Poleward-moving warm ocean currents have a moderating effect on high-latitude locations in the winter months. By contrast, equatorward-moving cold ocean currents exert their greatest influence in the tropics and middle latitudes.



7.8 El Niño, La Niña, and the Southern Oscillation

LO 8 Describe the Southern Oscillation and its relationship to El Niño and La Niña. List climate impacts of El Niño and La Niña.

Key Terms

El Niño

La Niña

Southern Oscillation

teleconnection

- El Niño refers to episodes of ocean warming in the eastern Pacific along the coasts of Ecuador and Peru. It is associated with weak trade winds, a strong eastward-moving equatorial countercurrent, and diminished upwelling along the western margin of South America.
- A La Niña event is associated with colder-than-average sea surface temperatures in the eastern Pacific. La Niña is linked to strong trade winds, a strong westward-moving equatorial current, and a strong Peru Current with significant coastal upwelling.
- El Niño and La Niña events are part of the global circulation and are related to a seesaw pattern of atmospheric pressure between the eastern and western Pacific called the Southern Oscillation.
- El Niño and La Niña events influence weather on both sides of the tropical Pacific Ocean as well as weather in the United States.

Exercises and Online Activities

Mastering Meteorology™

For instructor-assigned homework, test prep resources, and other learning materials, visit **Mastering Meteorology.**

Review Questions

1. Define *planetary-scale winds*.
2. What factors determine the scale of wind systems?
3. List some examples of microscale wind systems.
4. Describe the formation of each of the following: sea breeze, land breeze, valley breeze, and mountain breeze.
5. Explain how chinook (foehn) winds differ from katabatic (fall) winds.
6. What are the Santa Ana winds? How are they generated?
7. What is a country breeze?
8. Sketch the three-cell model of global circulation. Include the following: ITCZ, equatorial low, trade winds, subtropical highs, westerlies, subpolar lows, polar easterlies, polar high.
9. Label the wet regions and dry regions predicted by the three-cell model of global circulation you drew in Question 8.
10. Describe the locations of semipermanent cell of high and low pressures found in the Northern Hemisphere.
11. Explain why some wet and dry regions found in Figure 7.12 do not match up with those predicted by the three-cell model of global circulation.
12. Define *monsoon*, and explain its formation.
13. What is the North American monsoon, and how does it form?
14. Explain the forces that create the prevailing westerly winds in the midlatitudes.
15. What is a jet stream?
16. How does formation of the polar jet stream differ from formation of the subtropical jet stream?
17. What role do Rossby waves in the jet stream play in distributing heat?
18. Explain the relationship between global circulation and ocean currents.

19. What is upwelling? Where is it most likely to occur?

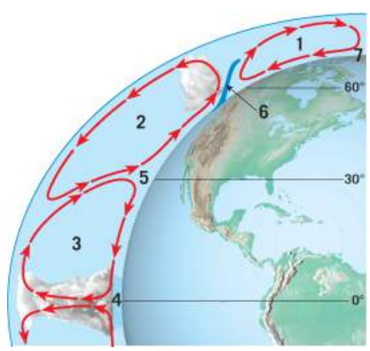
20. Compare El Niño, La Niña, and normal conditions.

21. What is a teleconnection?

22. List the major impacts of El Niño and La Niña.

Give It Some Thought

1. It is a warm summer day, and you are shopping in downtown Chicago, just a few blocks from Lake Michigan. All morning the winds have been calm, suggesting that no major weather systems are nearby. By midafternoon, should you expect a cool breeze from Lake Michigan or a warm breeze originating from the rural areas outside the city?
2. Boulder, Colorado, in the eastern foothills of the Rocky Mountains, is experiencing a warm, dry January day with strong westerly winds. What type of local winds are likely responsible for these weather conditions?
3. Which of the local winds described in this chapter is not heavily dependent on differences in the rates at which various ground surfaces are heated?
4. The accompanying sketch shows the three-cell circulation model in the Northern Hemisphere. Match the appropriate number on the sketch to each of the following features:



   - **a.** Hadley cell
   - **b.** Equatorial low
   - **c.** Polar front
   - **d.** Ferrel cell
   - **e.** Subtropical high
   - **f.** Polar cell

g. Polar high

5. If Earth did not rotate on its axis and if its surface were completely covered with water, what direction would a boat drift if it started its journey in the middle latitudes of the Northern Hemisphere? (*Hint:* What would the global circulation pattern be like for a nonrotating Earth?)

6. Briefly explain each of the following statements that relate to the global distribution of surface pressure:

a. The only true zonal distribution of pressure exists in the region of the subpolar low in the Southern Hemisphere.

b. The subtropical highs are stronger in the North Atlantic in July than in January.

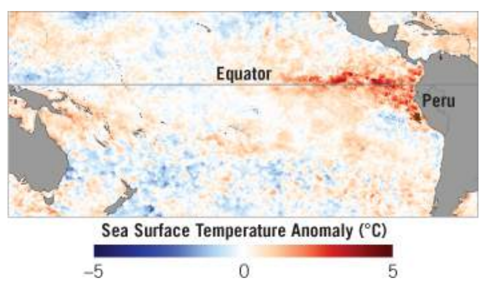
c. The subpolar lows in the Northern Hemisphere are the result of individual cyclonic storms that are more common in the winter.

d. A strong high-pressure cell develops in the winter over northern Asia.

7. On the accompanying image of Jupiter, notice the many zones of clouds that are produced by large convective cells similar to the Hadley cells on Earth. Given your understanding of the role of the Coriolis force in producing Earth's wind belts, do you think Jupiter rotates faster or more slowly on its axis than Earth? Explain.

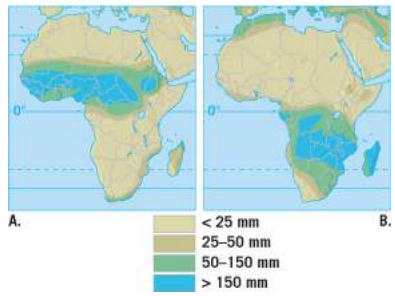
Jupiter (NASA)

8. Refer to Figure 7.12, and Figure 7.10, to determine what aspect of global circulation (polar highs, equatorial low, etc.) is responsible for each of the following:
    a. Dry conditions over North Africa
    b. The wet summer monsoon over Southeast Asia
    c. Dry conditions over west-central Australia
    d. Wet conditions over northeastern South America
9. Explain why the west coasts of continents generally experience cold ocean currents. How do these cold currents contribute to desert conditions in some coastal areas, such as the Atacama region of Peru?
10. The accompanying map shows sea-surface temperature anomalies (difference from normal) over the equatorial Pacific Ocean. Based on this map, answer the following questions:



    a. In what phase was the Southern Oscillation (El Niño or La Niña) when this image was made?
    b. Would the trade winds be strong or weak at this time?
    c. If you lived in Australia during this event, what weather conditions would you expect?
    d. If you were attending college in the southeastern United States during winter months, what type of weather conditions would you expect? (*Hint:* See Figure 7.27.)
11. Refer to Figure 7.12 to determine the average number of inches of precipitation received annually in the area in which you reside.

12. The accompanying maps of Africa show the distribution of precipitation for July and January. Which map represents July, and which represents January? How did you determine your answer?



Beyond the Textbook

1. Sea-Surface Temperature

Satellites are used to measure sea-surface temperatures (SST) in the equatorial Pacific Ocean. These data are then used to predict the development of El Niño or La Niña events.

Go to the Unisys Weather page at http://weather.unisys.com/. Click on Surface Data under Analyses, and then click on Daily Plots under Other Pages in the box on the upper right. Then click on SST Data to bring up a current sea-surface temperature map.

1. Where are the warmest waters? The coldest?
2. Are temperatures off the west coast of equatorial South America slightly warmer or colder than surrounding water?
3. Based on the temperature pattern, from which direction are surface winds blowing in the equatorial Pacific Ocean? How can you tell?
4. Describe the location of at least two warm ocean currents and two cold currents. (*Hint*: Look along the coasts of the continents—warm currents carry warm water poleward, and cold currents carry cold water equatorward.)

Click on SST Anom in the Plot field above the map to display the sea-surface temperature anomalies map. These anomalies are the difference between the current sea-surface temperatures and the 1981–2010 average temperatures.

5. Are the temperatures in the western part of the equatorial Pacific Ocean (directly north of Australia) warmer or colder than average?
6. Are the temperatures in the eastern part of the equatorial Pacific Ocean (off the coast of South America) warmer or colder than

average?

7. Estimate the number of degrees difference (in °C) between the current and average temperatures for the western and eastern regions.
8. Based on what you know about the Southern Oscillation, is the eastern equatorial Pacific Ocean currently exhibiting El Niño, La Niña, or normal characteristics?

2. Southern Oscillation Index†

Go to NOAA's Southern Oscillation Index (SOI) page at https://www.ncdc.noaa.gov/teleconnections/enso/indicators/soi/. After reading the introductory section, answer the following:

1. What is the SOI?
2. Explain how sea-level pressure is related to the temperature patterns associated with El Niño and La Niña.
3. According to the chart, has the SOI been predominately positive or negative in the last few months? Does this indicate El Niño or La Niña conditions?
4. Expand the data table by clicking the link located below the graph. Go to the bottom of the first table shown to find the most recent data. Is the SOI positive or negative for the most recent month? How many months has the SOI been in this phase?
5. Does this match your prediction from Part A, Question h? Why or why not?

†Adapted from *Geosystems* by Robert Christopherson/Pearson Education.

Chapter 8 Air Masses

This satellite view of Lake Superior and Lake Michigan illustrates what happens when a frigid, cloudless air mass from Canada moves across the lakes. Notice the narrow white bands of snow along the downwind shores of the lakes.

Focus on Concepts

Each statement represents the primary learning objective for the corresponding major heading within the chapter. After you complete the chapter, you should be able to:

1. Define *air mass* and *air-mass weather* (8.1).
2. List the basic criteria for an air-mass source region and identify the source regions that influence North America (8.2).
3. Summarize the weather conditions associated with the air masses that influence North America during the summer and winter (8.3).
4. Describe the processes by which traveling air masses are modified and discuss two examples (8.4).

Most people living in Earth's middle latitudes have experienced a hot, "sticky" heat wave consisting of several days of sultry weather that comes to an abrupt end marked by thunderstorms. The heat wave is then followed by a few days of relatively cool relief. This weather pattern features a period of generally uniform weather conditions, followed by a relatively short period of change and the subsequent reestablishment of a new set of weather conditions that might remain for several days before changing again. The cause of this weather pattern—air masses and their movement—is the main topic of this chapter.

8.1 What Is an Air Mass?

LO 1 Define *air mass* and *air-mass weather*.

An **air mass** is an immense body of air, usually 1600 kilometers (1000 miles) or more across and several kilometers thick, characterized by generally uniform conditions (Figure 8.1). In particular, the temperature characteristics, moisture content, and stability across the horizontal extent of an air mass are similar. When an air mass moves out of its region of origin, it carries these temperature and moisture conditions elsewhere, eventually affecting a much larger area.

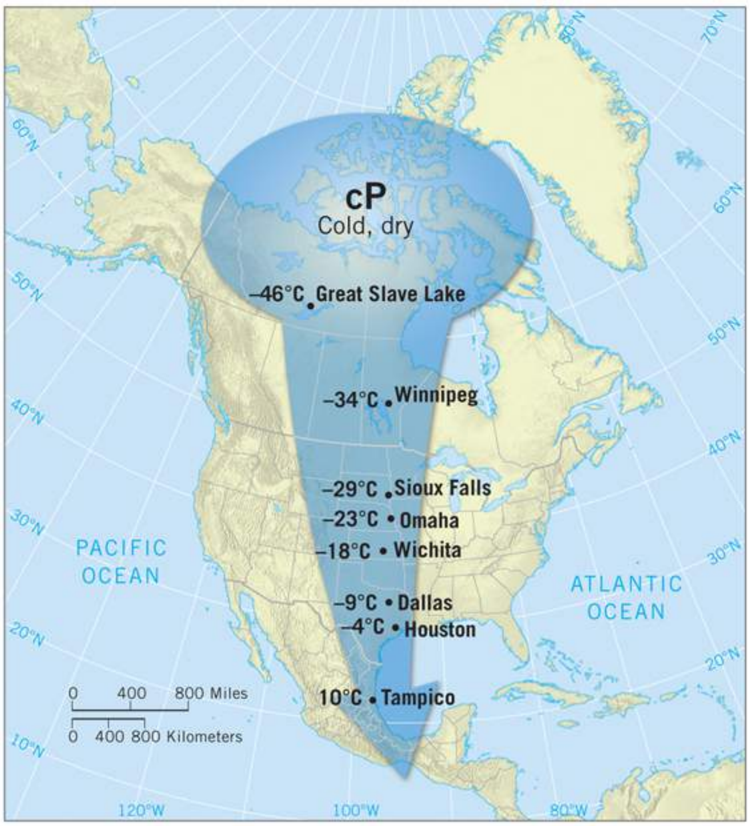
Figure 8.1 North Africa's Sahara Desert

Air masses that form over land areas in the subtropics are hot and dry.

How an air mass can influence weather is illustrated in Figure 8.2, where a cold, dry mass from northern Canada moves southward. At its source, near Great Slave Lake in northern Canada, its air temperature is a bitter −46°C (−51°F). By the time the air mass reaches Winnipeg, it is still a chilly –33°C (–27°F). Throughout its journey, it brings some of the coldest weather to places in its path, while the air mass itself becomes warmer as it moves southward through the Great Plains and into Mexico. Thus, an air mass impacts the weather in the areas over which it moves, but it is also modified in the process.

Figure 8.2 **Frigid Canadian air mass**

As this air mass moved southward, it brought some of the coldest winter weather to the areas in its path. The air mass gradually got warmer as it moved out of Canada. Thus, the air mass was modified while it modified the weather in the areas over which it moved.



> An air mass is a large body of air having generally uniform conditions of temperature, moisture, and stability.

The characteristics of an air mass are not perfectly uniform because these features blanket such a vast area. Consequently, different locations under the influence of an air mass experience some differences in temperature and humidity. Still, the differences observed throughout an air mass are small in comparison to the change experienced along an air-mass boundary—a comparatively narrow zone called a *front*. A front is a boundary separating air masses having different densities, which result from differences in temperature and moisture content. Fronts are discussed in the next chapter.

Because it may take several days for an air mass to traverse an area, the region under its influence is likely to experience generally constant weather conditions, a situation called **air-mass weather**. The air-mass concept is an important one because these vast air masses can affect our daily weather for several days in succession, and when they move, they often trigger stormy weather. For example, most strong middle-latitude disturbances originate along the frontal boundaries that separate air masses.

> Although some variations in temperature and moisture occur within an air mass, the characteristics of one air mass are quite unlike those in an adjacent air mass.

Concept Checks 8.1

- Define *air mass*.
- What is *air-mass weather*?

8.2 Classifying Air Masses

LO 2 List the basic criteria for an air-mass source region and identify the source regions that influence North America.

Where do air masses form, and how are they classified? These basic questions are closely related because the area over which an air mass forms vitally affects the properties that characterize it and its resulting classification.

Source Regions

The areas in which air masses originate are called **source regions**. Because the atmosphere is heated chiefly from below and gains its moisture by evaporation from Earth's surface, the nature of the source region largely determines the characteristics of an air mass. Ideally, a source region should meet two criteria. First, it should be an extensive, uniform area. A region having highly irregular topography or one that has a surface consisting of both large areas of water and land will not create uniform characteristics in the air above it.

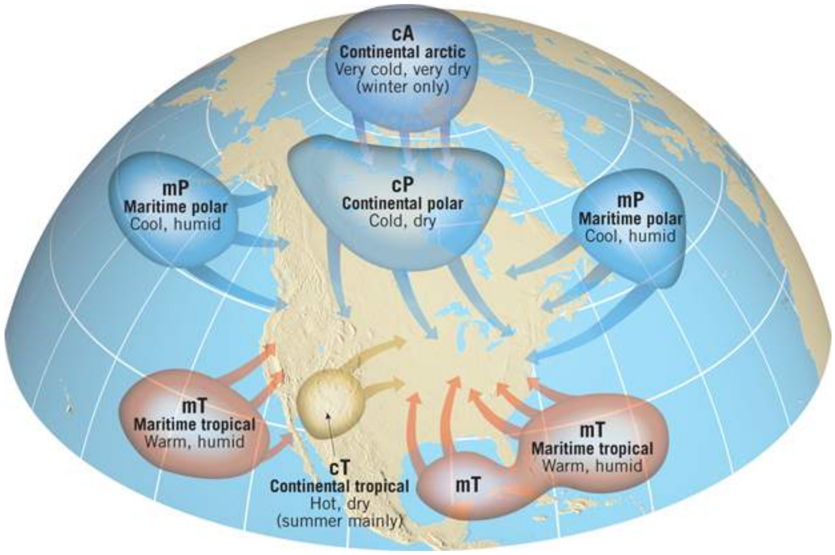
The second criterion is that the air masses form in regions where atmospheric circulation is relatively stagnant, so that air stays over the region long enough to reach some degree of equilibrium with the surface. Stated another way, regions dominated by stationary or slow-moving high-pressure systems (anticyclones), which tend to have light winds or be calm, are the sites where most, but not all, air masses develop.

> Air masses form when air is stagnant over large areas and take on the characteristics of the water or land surface beneath them.

Figure 8.3 shows the source regions that produce the air masses that most often influence North America. The waters of the Gulf of Mexico and Caribbean Sea and similar regions in the Pacific Ocean west of Mexico yield warm, humid air masses. The land area that encompasses the southwestern United States and northern Mexico also produces a warm air mass, but with much lower humidity. In contrast, the North Pacific and the North Atlantic produce cool, humid air masses, and the snow- and ice-covered areas comprising northern North America and the adjacent Arctic Ocean produce cold, dry air masses.

Figure 8.3 Air-mass source regions for North America

Arrows show the common paths that air masses follow as they move out of their source regions.



As you might expect, the size of the source regions and the temperature of the surface change seasonally. Air mass movement also varies seasonally. In the summer, warm, moist air masses tend to move from oceans toward land. Also during the summer, when the days are longer and the Sun's heating is more intense, warm air masses move much farther poleward than during the winter. Conversely, cold, dry air masses move much farther equatorward in the winter and tend to move off the continents on which they form.

Notice in Figure 8.3 that major source regions are not found in the middle latitudes, but instead are confined mainly to subtropical, subpolar, and polar locations. The middle latitudes, in contrast to these other regions, are dominated by atmospheric circulation patterns (midlatitude cyclones, the topic of Chapter 9) that cause cold and warm air masses to clash. As a result, the middle latitudes lack the stagnation necessary for a source region. Instead, the midlatitudes are one of the stormiest regions on the planet.

> Air masses do not generally form in the middle latitudes because this region experiences a variety of fast-changing weather patterns, rather than supporting stagnant air.

Air-Mass Classification

The classification of an air mass depends on the latitude of the source region and the nature of the surface—oceanic verses continental. The latitude of the source region mainly determines temperature conditions and, to a lesser degree, moisture content, whereas the nature of the surface strongly influences the moisture content of the air. For example, polar regions tend to produce cold and dry air masses, while tropical oceans generate warm and moist air masses.

Air masses are identified by two-letter codes. Based on temperature, air masses are placed into one of three categories: **polar (P) air mass**, **arctic (A) air mass**, or **tropical (T) air mass**. The temperature differences between polar and arctic are usually small and simply serve to indicate the degree of coldness of the respective air masses.

The lowercase letter **m** (for **maritime air mass**) or the lowercase letter **c** (for **continental air mass**) is used to designate the nature of the surface in the source region and, hence, the humidity characteristics of the air mass. Because maritime air masses form over oceans, they have a high water-vapor content compared to continental air masses that originate over land. When this classification scheme is applied, the following air masses can be identified:

cA	continental	arctic
cP	continental	polar
cT	continental	tropical
mT	maritime	tropical
mP	maritime	polar

Notice that the list does not include mA (maritime arctic) because such air masses seldom, if ever, form. Although arctic air masses form over the Arctic Ocean, this water body is largely covered with ice throughout the year. Consequently, the air masses that originate here consistently have the moisture characteristics of a continental source region.

Concept Checks 8.2

- What two criteria must be met for an area to be an air-mass source region?
- Why are regions that have a cyclonic circulation generally not conducive to air-mass formation?
- Compare the temperature and moisture characteristics of the following air masses: cA, cP, mP, mT, and cT.

8.3 Properties of North American Air Masses

LO 3 Summarize the weather conditions associated with the air masses that influence North America during the summer and winter.

After an air mass forms, atmospheric circulation patterns eventually cause it to migrate from the area where it acquired its distinctive properties to a region with different surface characteristics. This means that the day-to-day weather we experience often depends on the temperature, moisture content, and the stability of the large bodies of air that traverse our location. In this section, we examine the properties of the principal air masses with source regions in North America as well as those that directly influence our daily weather. Table 8.1 serves as a useful resource.

Table 8.1 Weather Characteristics of North American Air Masses

Air Mass	Source Region	Temperature and Moisture Characteristics in Source Region	Stability in Source Region	Associated Weather upon Reaching the United States
cA	Arctic Ocean (ice covered) and Greenland ice cap	Bitter cold and very dry (winter only)	Stable	Bitter cold in winter
cP	Interior Canada and Alaska	Very cold and dry in winter Mild (warm) and dry in summer	Stable entire year	a. Cold spells in winter; brings lake-effect snow to leeward shores of Great Lakes b. Comparatively cool, mild summer conditions
mP	North Pacific	Mild (cool) and humid entire year	Unstable in winter Stable in summer	a. Low clouds and showers in winter; heavy orographic precipitation on windward side of mountains b. Low stratus and fog along coast in summer
mP	Northwestern Atlantic	Cold and humid in winter Cool and humid in summer	Unstable in winter Stable in summer	a. Occasional nor'easter in winter b. Occasional periods of clear, cool weather in summer
cT	Northern Mexico and southwestern United States	Hot and dry (mainly summer)	Unstable	Hot, dry, and cloudless; brings occasional drought to southern Great Plains
mT	Gulf of Mexico, Caribbean Sea, western Atlantic	Warm and humid entire year	Unstable entire year	a. Widespread precipitation or advection fog in winter b. Hot and humid conditions in summer, with frequent cumulus development, and showers or thunderstorms
mT	Eastern subtropical Pacific	Warm and humid entire year	Stable entire year	a. Brings fog, drizzle, and occasional moderate precipitation to northwestern Mexico and western United States in winter b. Occasionally reaches the western United States in summer and is a source of moisture for thunderstorms

Continental Polar (cP) and Continental Arctic (cA) Air Masses

Continental polar (cP) and continental arctic (cA) air masses are cold and dry. In the winter, continental polar air originates over the snow-covered interior regions of Canada and Alaska, poleward of 50° north latitude. Continental arctic air forms even farther north, over the Arctic Ocean, which is frozen most of the year, and the Greenland ice cap (see Figure 8.3). Lower temperatures distinguish cA air from cP air—although the differences may be slight.

Winter Characteristics

During the winter, both cP and cA air masses are bitterly cold and very dry. Winter nights in the source region are long, and the daytime Sun is short-lived and low in the sky. Consequently, as winter advances, Earth's surface and atmosphere lose heat that is not replenished by incoming solar energy. Therefore, the surface is very cold, and the air near the ground is gradually chilled to heights of 1 kilometer (0.6 mile) or more. The result is a strong and persistent temperature inversion, in which the coldest temperatures are found near the ground. Because the air is very cold and the surface below is frozen, the water vapor content of these air masses is extremely low. As a result, these air masses are very stable and produce clear blue skies and very cold conditions (Figure 8.4).

Figure 8.4 Continental polar (cP) air mass invades Vermont

As cP or cA air moves from its source region, it carries cold, dry weather to the United States, normally entering between the Great Lakes and the Rockies. Because there are no major mountainous barriers between the high-latitude source regions and the Gulf of Mexico, cP and cA air masses can sweep rapidly and with relative ease far southward into the United States. The winter cold spells experienced in much of the central and eastern United States are closely associated with these polar outbreaks. One such cold spell is described in Severe & Hazardous Weather 8.1.

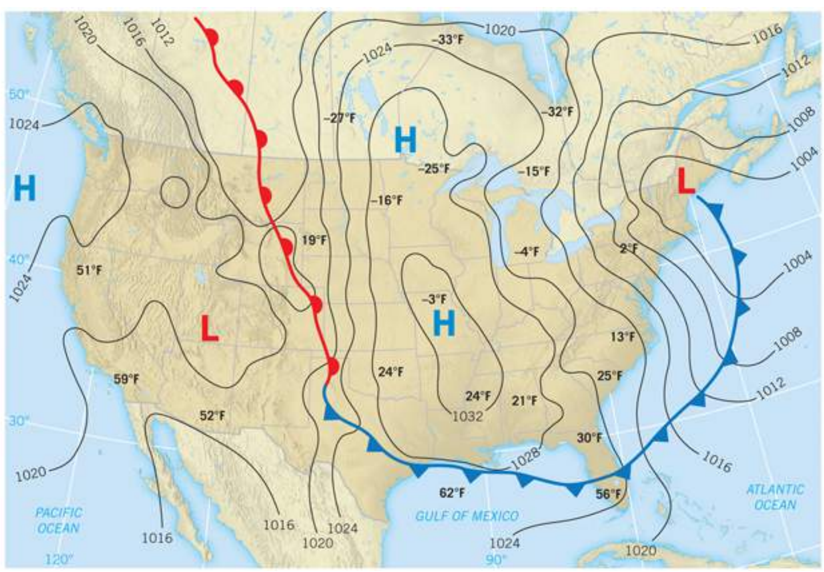
Severe & Hazardous Weather 8.1

The Siberian Express

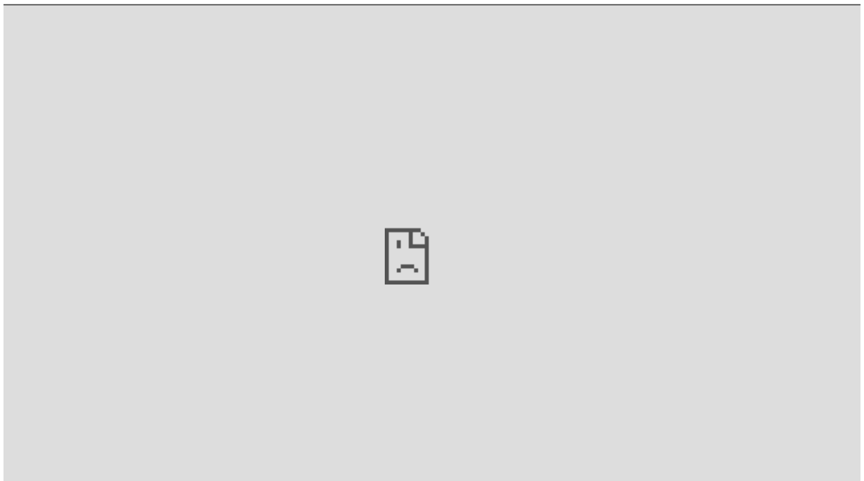
The surface weather map for February 19, 2015, shows a large high-pressure center covering the eastern two-thirds of the United States and a substantial portion of Canada (Figure 8.A). This was the third outbreak of arctic air invading the United States that February. As is usually the case in winter, a large anticyclone such as this is associated with a huge mass of dense and bitterly cold arctic air. Once an air mass forms over the frozen expanses near the Arctic Circle, the wavy flow in the jet stream often directs it southward (see Figure 7.23,). When an outbreak of this type occurs, it is popularly called the "Siberian Express" by the news media, even though the air mass does not originate in Siberia.

Figure 8.A **Invasion of arctic air**

Shown is a surface weather map for 7 a.m. EST, February 19, 2015. This simplified National Weather Service (NWS) map shows an intense winter cold spell caused by an outbreak of frigid continental arctic air.



Watch **Video: Lake Effect Snow**

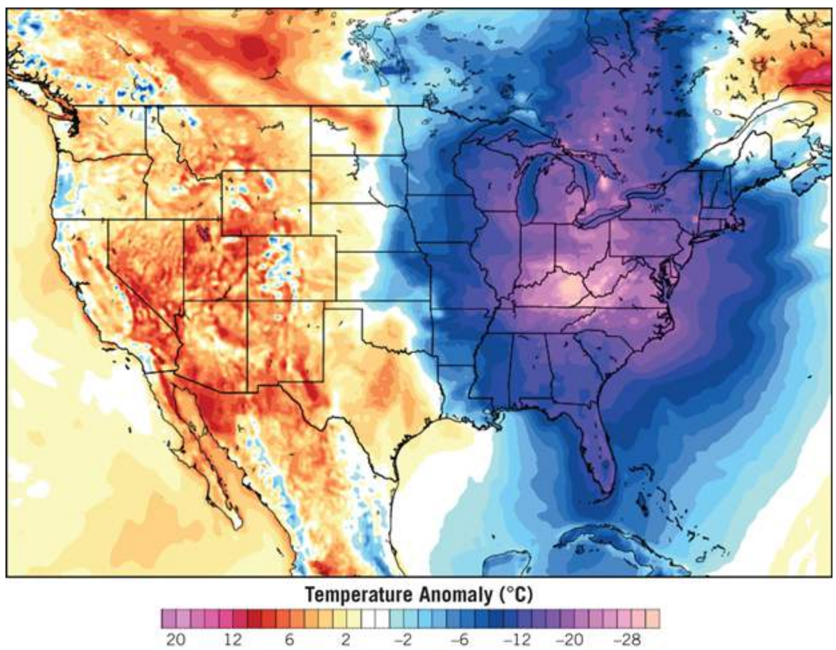


By morning of February 20, as the frigid mass of cold air advanced southward, hundreds of record low temperatures had been set in eastern U.S. cities including New York, Pittsburgh, Baltimore, Atlanta, and Washington, D.C. Cleveland broke its all-time record low for the month of February, with a temperature of −17°F. A new, all-time record low for any month was recorded in Lynchburg, Virginia, with a temperature of −11°F. The town of Cotton, Minnesota, logged the nation’s low at −43°F.

The temperature anomaly map in Figure 8.B shows the extent of this cold snap. Notice that locations in the eastern half of the United States and parts of southeastern Canada have temperatures that are at least 4°C below normal, and some locations experienced conditions exceeding 28°C degrees below normal for this date. Hypothermia claimed the lives of at least 22 people as an arctic blast continued to push through the central and eastern parts of the United States.

Figure 8.B A cold snap in the Midwest and East

This map shows temperature anomalies (°C) for North America for February 20, 2015—the day after the weather map in Figure 8.A was generated. *Anomaly* refers to the departure from what is expected. In this case, the map shows departures from the average temperatures based on 1981–2010 averages. Whereas the Midwest and East were much colder than average, notice that the West was considerably warmer than average.



Weather Safety

During extremely cold and snowy weather, the safest thing to do is stay indoors. If you must travel, be sure to check road conditions, let someone know where you are going, and keep a winter safety kit in your car. Your winter weather safety kit should contain the following:

- Water and nonperishable food items
- Flashlight, cell phone, and charger
- First-aid kit, extra blankets, and warm clothes

If your car gets stuck in frigid weather, stay with the car! It's very easy to get disoriented in blowing snow if you leave the car. Clear snow from the exhaust pipe, and run the engine about 10 minutes every hour to stay warm. Keep the window cracked while the engine is running to avoid carbon monoxide poisoning.

Apply What You Know

1. What air mass (classification) was most likely associated with this event?
2. Describe how this type of air mass forms.

You might have wondered . . .

When a cold air mass moves south from Canada into the United States, how rapidly can temperatures change?

When a fast-moving frigid air mass advances into the northern Great Plains, temperatures can plunge 40° to 50°F in just a few hours. One notable example is a drop of 100°F, from 44° to –56°F, in 24 hours at Browning, Montana, on January 23–24, 1916.

Summer Characteristics

Because cA air is a winter phenomenon, only cP air has any influence on our summer weather. The properties of the source region for cP air in summer are very different from those during winter. Instead of being chilled by the ground, the air over Canada is warmed from below as the long days and higher Sun angle warm the snow-free land surface. Although summer cP air is warmer and has a higher moisture content than its wintertime counterpart, the air is still cool and relatively dry compared to air in the United States. Summer heat waves in the central and eastern United States often end with the southward advance of cP air, which brings cooling relief and pleasant weather for a day or two.

> Continental polar (cP) and continental arctic (cA) air masses are bitterly cold and dry in the winter, while cP air masses bring pleasant conditions to the United States in the summer.

Maritime Polar (mP) Air Masses

Maritime polar (mP) air masses are cold and moist and form at high latitudes over cold ocean waters. But compared with cP air masses in winter, mP air is relatively mild because the ocean surface is significantly warmer than the adjacent landmasses. The temperature of mP air masses also tends to moderate more quickly as the air moves equatorward.

Two regions are important sources for mP air that influences North America: the Pacific Ocean west of Alaska, and the northwestern Atlantic off the coast of Newfoundland (see Figure 8.3). Because of the general west-to-east atmospheric circulation in the middle latitudes, mP air masses from the North Pacific source region has a greater influence on North American weather, especially in the winter, than mP air masses originating in Atlantic waters. Air masses that form in the northwestern Atlantic tend to move eastward and impact the weather in Europe.

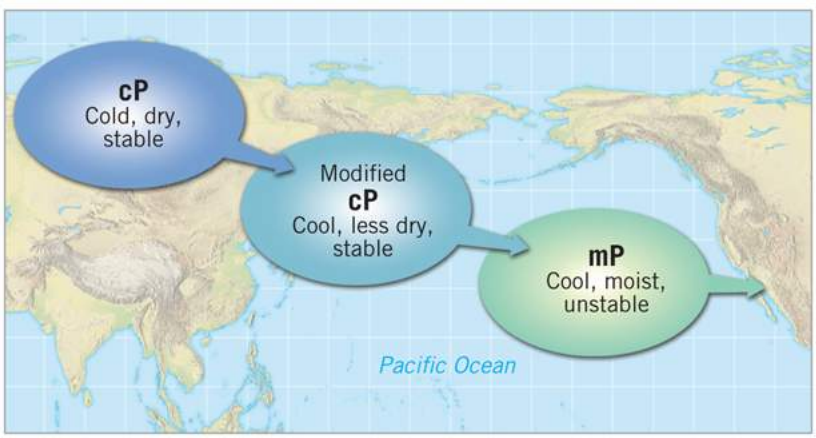
> Maritime polar (mP) air masses are cool and moist.

Pacific mP Air Masses

During the winter, mP air masses that form over the Pacific often begin as cP air in Siberia (Figure 8.5). Although air rarely stagnates over the northern Pacific Ocean, this source region is vast enough to allow the air moving across it to acquire the characteristics of an mP air mass. As the air advances southeastward over the relatively warm Pacific water, evaporation adds moisture, while surface heating warms its lower levels. Consequently, what began as a very cold, dry, and stable air mass evolves into one that is cool, humid, and relatively unstable.

Figure 8.5 Formation of a Pacific mP air mass

During winter, maritime polar (mP) air masses in the North Pacific usually begin as continental polar (cP) air masses in Siberia. The cP air is modified to mP as it slowly crosses the ocean.



Most precipitation along the west coast of North America results from wintertime storms that pass across the Gulf of Alaska. These storms are dominated by humid, cool mP air. As this mP air arrives at the west coast, it is often accompanied by low clouds and shower activity. When the mP air advances inland and reaches the western mountains, orographic uplift can produce heavy rain or snow on windward slopes.

Summer brings a change in the characteristics of mP air masses. During the warm season, the ocean is cooler, rather than warmer, than the surrounding continents. In addition, a Pacific high-pressure cell lies off the western coast of the United States (see Figure 7.11B,). Consequently, there is almost continuous eastward flow of cool air off the Pacific. Although the air near the surface may be conditionally unstable, the presence of high pressure means that there is subsidence and stability aloft. Thus, low stratus clouds and fogs characterize the summer weather over the ocean along much of the western coast of the United States (see Figure 5.10,).

> Most wintertime precipitation along the west coast of North America results from invasions of mP air masses from the Pacific.

As this cool mP air moves inland, it is heated at the surface. Heating of this air mass from below results in turbulence that acts to reduce the relative humidity in the lowermost layers. This in turn causes the clouds, or fog, to dissipate, producing abundant sunshine and mild conditions in coastal locations.

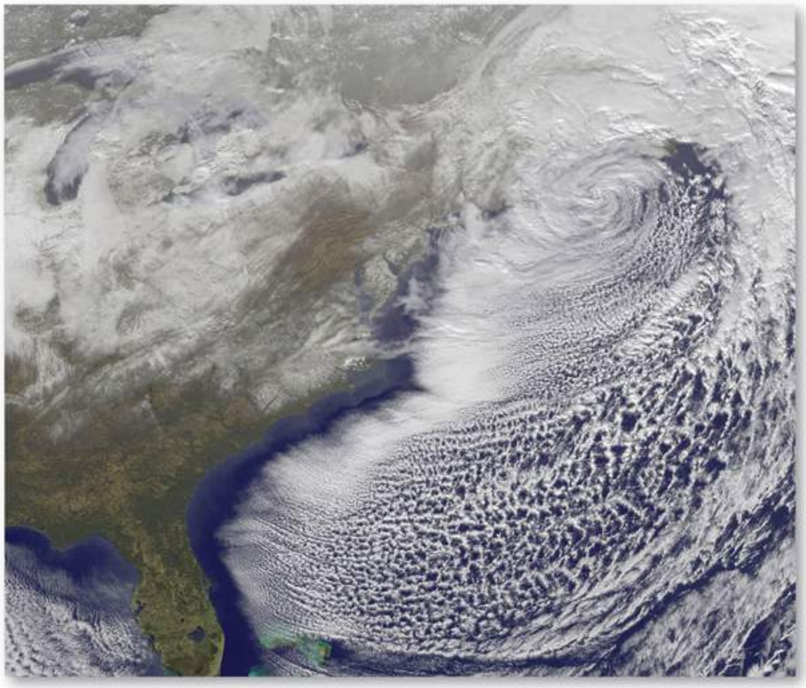
Maritime Polar Air from the North Atlantic

Air masses forming in the northwestern Atlantic source region only occasionally affects the weather of North America. Nevertheless, these air masses can have a dramatic effect on the northeastern United States when a passing low-pressure center (midlatitude cyclone) pulls mP air into the region as it rotates counterclockwise. In winter, these cyclonic winds can be particularly strong.

The weather associated with a wintertime invasion of mP air from the Atlantic is known as a **nor'easter**. Strong northeast winds, freezing or near-freezing temperatures, high relative humidity, and the likelihood of precipitation make this weather phenomenon an unwelcome event. Fortunately, its influence is generally confined to the area east of the Appalachians and north of Cape Hatteras, North Carolina.

Eye on the Atmosphere 8.1

This satellite image from December 27, 2010, shows a strong winter storm off the east coast of the United States.



Apply What You Know

1. What air mass is being drawn into the storm to produce the dense clouds in the upper right?
2. What name is applied to a storm such as this?
3. Farther south, the cold air mass over the southeastern states is cloud free. What is its likely classification? Explain how it is being modified as it moves over the Atlantic.

A classic example is shown in Figure 8.6. This nor’easter moved up the east coast on January 12, 2011, dumping heavy snow on the New England states for the third time in as many weeks. The satellite image in Figure 8.6 shows that this cyclonic storm had a distinctive counterclockwise circulation around a low-pressure center. Cold, humid mP air from the North Atlantic was drawn toward the storm center, producing dense clouds, especially on the north and east sides of the storm. More than 61 centimeters (24 inches) fell in many areas. Blizzard conditions—with visibility reduced to less than 0.4 kilometer (0.25 mile) and gale-force winds lasting for more than 3 hours—developed in parts of Connecticut and Massachusetts.

Figure 8.6 Classic nor’easter

This NOAA image shows a strong nor’easter along the coast of New England on January 12, 2011. In winter, the strong northeast winds of a nor’easter carry cold, humid mP air from the North Atlantic into New England and the middle Atlantic states. The ground-level view of the storm in Boston shows that the combination of ample moisture and strong convergence can result in heavy snow.

Whereas mP air masses from the Atlantic may produce an unwelcome nor’easter during the winter, summertime incursions of mP air masses bring pleasant weather. Although infrequent, when the circulation pattern carries mP air into New England, occasionally as far south as Virginia, the region enjoys clear, cool weather and good visibility.

Maritime Tropical (mT) Air Masses

Maritime tropical (mT) air masses affecting North America most often originate over the warm waters of the Gulf of Mexico, the Caribbean Sea, and the adjacent western Atlantic Ocean (see Figure 8.3). The tropical Pacific is also a source region for mT air. However, the land area affected by this latter source is small compared with the size of the region influenced by air masses produced in the Gulf of Mexico and adjacent waters.

> Maritime tropical (mT) air masses are warm and moist.

Gulf–Caribbean–Atlantic mT Air Masses

Maritime tropical air masses from the Gulf–Caribbean–Atlantic source region greatly influence the weather of the United States east of the Rocky Mountains. Although the source region is dominated by the North Atlantic subtropical high, the air masses tend to be unstable because the source region is located on the weak western edge of the anticyclone, where pronounced subsidence is absent.

In midwinter, cP air masses tend to dominate the weather of central and eastern United States. Therefore, mT air invades the country less often in the winter than in the summer. When an invasion does occur, the lower portions of the air mass are chilled and stabilized as the air moves northward over the cold land. As a result, cloud formation and precipitation are unlikely. Widespread precipitation does occur, however, when a northward-moving mT air mass is pulled into a traveling cyclonic storm and forced to ascend. In fact, much of the wintertime precipitation over the eastern and central states results when mT air from the Gulf of Mexico is lifted along fronts in traveling cyclones.

Another weather phenomenon associated with a northward-moving wintertime mT air mass is advection fog. Dense fogs can develop as the warm, humid air is chilled as it moves over the cold land surface.

During the summer, mT air masses exert a strong influence on the weather east of the Rocky Mountains. These air masses are largely responsible for the hot and humid conditions that prevail over the eastern and central United States. Summertime mT air from the Gulf also tends to be unstable. As these air masses move inland, daytime heating of the surface layers further increases the air's instability. Because the relative humidity is high, only modest convective lifting is needed to bring about cloud development and thunderstorms (Figure 8.7).

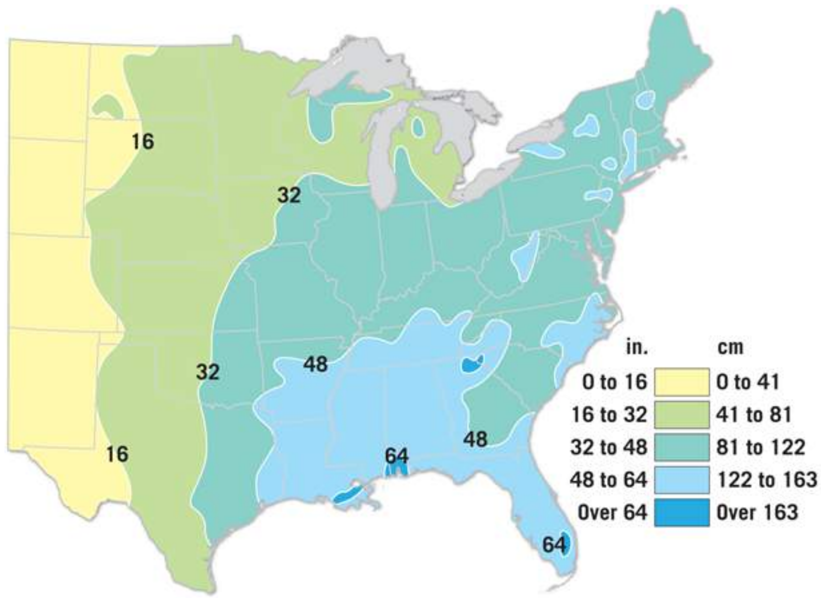
Figure 8.7 **Thunderstorm development in a moist, maritime tropical (mT) air mass**

Air masses from the Gulf and surrounding waters are the primary source of the precipitation in the eastern two-thirds of the United States. Tropical Pacific air masses contribute little to the water supply east of the Rockies because the western mountains effectively “wring dry” the moisture from the air through numerous episodes of orographic uplift.

The distribution of average annual precipitation for the eastern two-thirds of the United States can be shown by using **isohyets** (lines connecting places having equal rainfall), as illustrated in Figure 8.8. The pattern of isohyets shows the greatest rainfall in the Gulf region and a decrease in precipitation with increasing distance from the mT source region.

Figure 8.8 Average annual precipitation for the eastern two-thirds of the United States

Note that yearly precipitation totals generally decrease as one moves farther away from the Gulf of Mexico, the source region for mT air masses.



> Maritime tropical (mT) air masses from the Gulf and surrounding waters are the primary source of the precipitation in the eastern two-thirds of the United States.

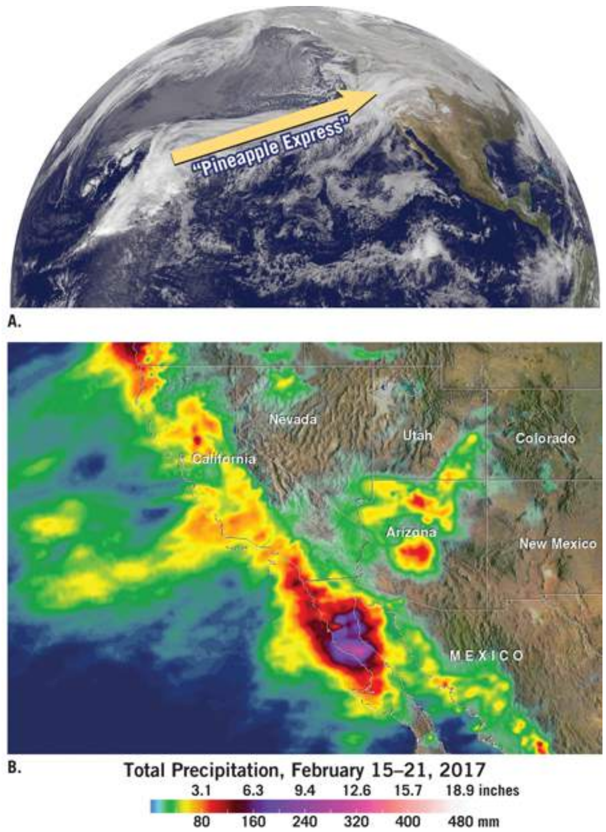
Pacific mT Air Mass

In the winter, air from the tropical Pacific affects the weather along coastal areas of northwestern Mexico and the southwestern United States. When this warm, moist air mass moves northeastward toward North America, cooling at the surface usually generates fog or low-lying stratus clouds that may produce drizzle or light rain. If the air mass is lifted over mountainous terrain, moderate precipitation may result.

There are times when mT air from the subtropical Pacific is associated with winter weather phenomena known as **atmospheric rivers**, narrow zones in the atmosphere that transport significant amounts of moisture to regions outside the tropics. One well-known example is popularly called the *Pineapple Express*. This atmospheric river is driven by a strong southern branch of the polar jet stream and transports humid, warm mT air from as far away as the Hawaiian Islands (Figure 8.9A). In the winter, this moist air can bring torrential rains to California and other west coast locations and produce heavy snows in the Sierra Nevada (Figure 8.9B).

Figure 8.9 Atmospheric river

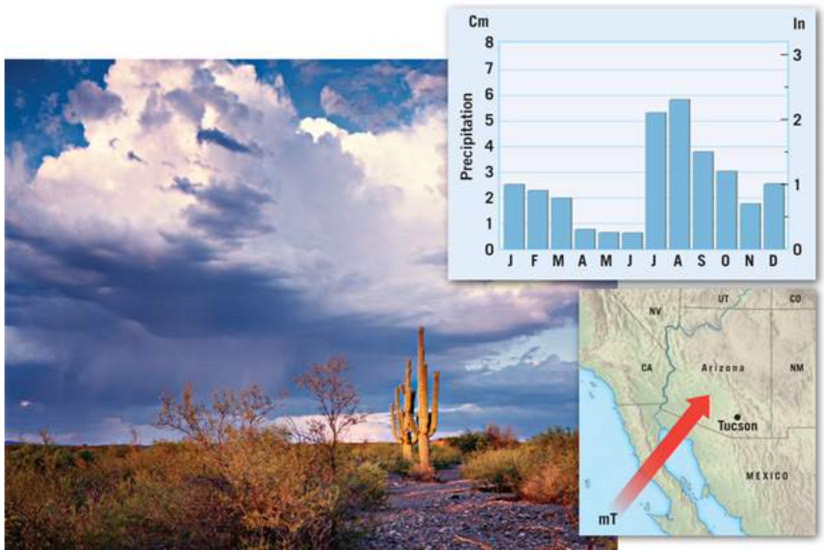
A. This satellite image of clouds over the Pacific Ocean illustrates the "Pineapple Express," a phenomenon in which a strong jet stream carries mT air from as far away as Hawaii to the West Coast. **B.** Rainfall estimates for the period February 15–21, 2017, from three surges of moisture carried by the Pineapple Express.



In summer, mT air moves northeastward from its Pacific source region up the Gulf of California and into the southwestern United States (see Figure 7.16,). This flow, which typically occurs in July and August, is monsoonal in character—the inflow of moist air is a response to thermally produced low pressure that develops over the extremely hot southwestern states. The July–August rainfall maximum for Tucson, Arizona, is a result of this incursion of Pacific mT air (Figure 8.10) caused by the North American monsoon.

Figure 8.10 **Summer monsoon in the Southwest**

The photo shows cumulonimbus clouds developing over the Sonoran Desert in southern Arizona on a July afternoon. The source of moisture for these summer storms is maritime tropical air from the eastern Pacific.



Continental Tropical (cT) Air Masses

Continental tropical (cT) air masses are more prevalent in summer when air over northern Mexico and adjacent parts of the arid southwestern United States is the hottest (see Figure 8.3). Because of the intense daytime heating at Earth’s surface, cT air is unstable—hot near the surface and significantly cooler aloft. Nevertheless, it generally remains nearly cloudless because of extremely low humidity and the presence of high pressure aloft that tends to limit convective lifting. The prevailing weather, therefore, is hot, with almost no rainfall. However, as we discussed earlier, by midsummer the intense heating of this source region creates a strong thermal low that, in July and August, draws in humid maritime tropical air from the Pacific to trigger a rainy season. The rain generated is often associated with strong thunderstorms that can cause flooding.

> Continental tropical (cT) air masses, mainly a summertime phenomenon, are hot and dry.

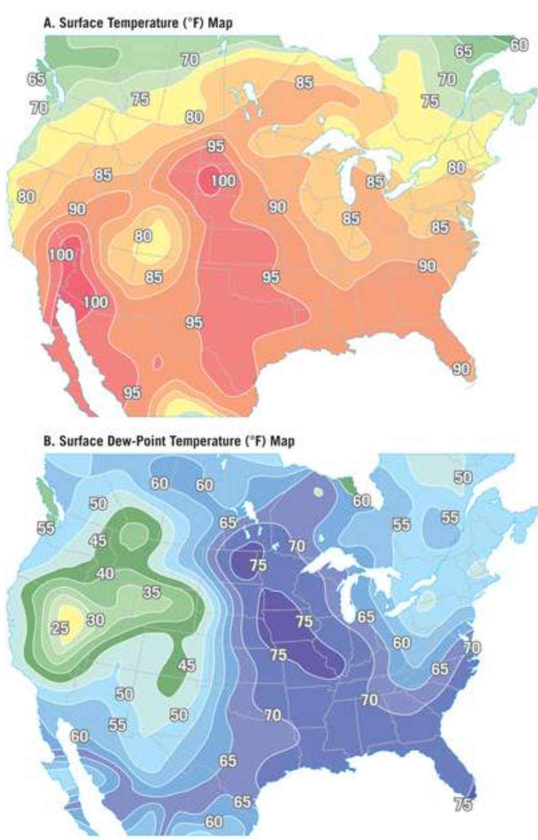
Although this cT air mass is usually confined to its source region, it occasionally moves into the southern Great Plains. When this occurs, the cT air may produce a *dryline*, a narrow zone that can trigger severe thunderstorms should it encounter a warm, moist maritime tropical air mass. Drylines are described in more detail in Chapters 9 and 10.

Identifying Air Masses on Weather Maps

On July 20, 2016, a large mT air mass advanced deep into the continental United States. It extended from Texas to Florida and northward to the Dakotas, eventually spilling into south-central Canada. Several locations in western South Dakota recorded high temperatures that exceeded 100°F (see Severe & Hazardous Weather 8.2). Maritime tropical air masses such as this are identified by their high temperatures and high humidity. The high surface air temperatures of this hot, moist air mass are shown on the weather map in Figure 8.11A.

Figure 8.11 Identifying air masses on weather maps

A. Surface temperature (°F) map for July 20, 2016. **B.** Dew-point temperature (°F) map for July 20, 2016.



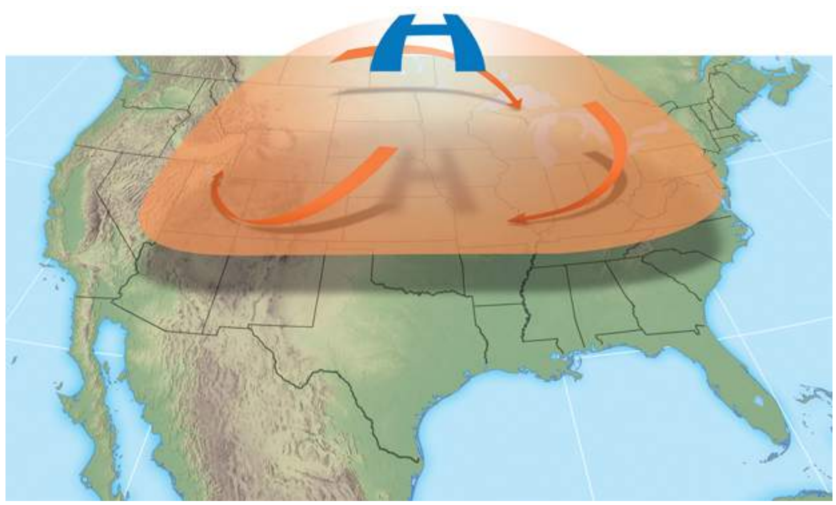
Severe & Hazardous Weather 8.2

Heat Wave of 2012

A heat wave forms when high pressure aloft strengthens and remains over a region for several days. The heat wave of 2012 lasted much longer—from late June until early August. This is common in summer, because summer weather patterns are generally slower to change than those in winter. In addition, when the wavy pattern of the polar jet swings northward in the summer, it pulls warm tropical air into the United States and Canada. This warm, moist air, under the influence of high pressure aloft—causing air to sink—acts to trap heat by preventing hot surface air from rising (Figure 8.C). Without lifting, there is little convection and therefore little chance of cloud development and precipitation. The result is clear skies and a continual buildup of heat at the surface, creating a *heat wave*.

Figure 8.C Heat waves are generated by high pressure aloft

When sinking air aloft remains over a region for several days to several weeks, it acts as a lid to prevent hot surface air from rising, resulting in a heat wave.



The heat wave of 2012 began in late June as high pressure aloft blanketed much of the eastern two-thirds of the United States. During this period Denver, Colorado, tied its all-time high temperature of 105°F. St. Louis, Missouri, and Paducah, Kentucky, both set all-time high temperature records of 108°F. Nashville, Tennessee, reached 118°F. By mid-July, St. Louis had endured 16 consecutive days with temperatures over 100°F. More than 8,000 high-temperature records were broken across the country. By early August, this heat wave had claimed 82 lives in the United States and Canada.

> Warm, moist air, under the influence of high pressure aloft, acts to trap heat by preventing hot, moist surface air from rising.

In the western part of the country, large wildfires raged in Utah, Wyoming, Montana, New Mexico, Arizona, and Idaho. Drought affected 80 percent of the contiguous United States and led to massive crop failures. Although this was the worst drought since the 1950s, it was not on the scale of the 1930s Dust Bowl.

The hot, moist air mass associated with this heat wave became sufficiently unstable on June 29, 2012, to set off a line of strong thunderstorms in the eastern part of the country, producing extremely strong winds called *derechos*. These winds, some exceeding 80 miles per hour, caused hundreds of millions of dollars in damage and disrupted electrical power for 3.7 million residents from eastern Indiana to the Atlantic Seaboard. These storms resulted in another 22 deaths. A week later, over 500,000 people were still without power as the heat wave continued.

WEATHER SAFETY

Between 1986 and 2015, an annual average of 130 heat-related deaths occurred in the United States. This is higher than any other weather-related hazard. Excessive heat can result in heat exhaustion, heat stroke, or even death. The first sign of heat-related illness is usually a headache, followed by rapid pulse or shallow breathing.

There are a number of things you can do to stay safe in the heat:

- Drink plenty of water.
- Stay indoors in air conditioning during the hottest part of the day.
- Avoid doing strenuous work during the heat of the day.
- Avoid getting too much sun.

Apply What You Know

1. What is a heat wave?
2. How can you stay safe during periods of extreme heat?

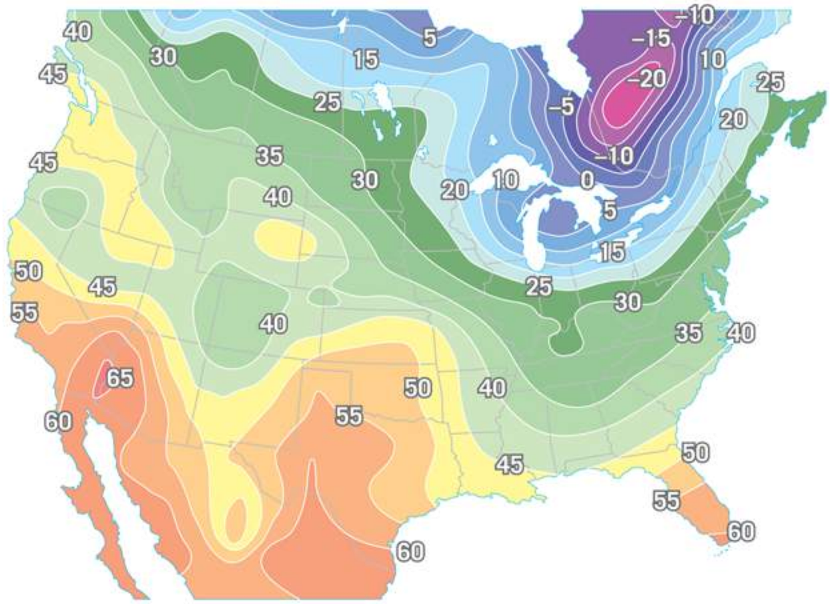
To determine the humidity of an air mass, meteorologists usually examine dew-point temperatures, like those displayed on the map for this date (Figure 8.11B). Recall from Chapter 4 that air having a dew-point temperature exceeding 65°F (18°C) is considered humid, whereas air with a dew-point temperature above 75°F (24°C) is considered oppressive. Stated another way, the closer the dew-point temperature is to the air temperature, the higher the relative humidity. When the temperature and the dew point are the same, the air is saturated, and the relative humidity is 100 percent. Notice in Figure 7.11B that much of the midsection of the United States had dew-point temperatures exceeding 65°F and, in some regions, over 75°F—a clear indication of high humidity.

By contrast, notice that the southwestern United States also experienced high temperatures on this date (Figure 8.11A). However, dew-point temperatures in the southwest, as shown on Figure 8.11B, ranged from less than 25°F to about 50°F, an obvious sign of much dryer air. The air mass over the southwestern states is therefore classified as continental tropical (cT)—hot and dry—whereas the air mass located in the midsection of the country is classified as maritime tropical (mT) because of its high temperature and high humidity.

> Meteorologists usually examine dew-point temperatures to determine the moisture content of an air mass.

A continental polar (cP) air mass moving southward into the United States can be easily identified on a surface temperature map like the one in Figure 8.12. We know it is a polar air mass because of its extremely cold core. But how do we know that this air mass is dry, as compared to a moist mP air mass that originated over the North Atlantic, without knowing its dew-point temperatures? Recall that extremely cold air has a low capacity to hold moisture. You can be confirm this by examining Table 4.1 , which shows that 40°C (104°F) air requires more than 10 times more moisture to reach saturation than air at 0°C (32°F). Therefore, any bitterly cold air mass must also be extremely dry and could not have formed over an open ocean before moving inland.

Figure 8.12 **Identifying a continental polar (cP) air mass using a surface temperature map**



Concept Checks 8.3

- Which two air masses have the greatest influence on weather east of the Rocky Mountains? Explain your choice.
- Which air mass influences the weather of the Pacific Coast more than any other?
- Which air mass and source region provide the greatest amount of moisture to the eastern and central United States?
- How can a weather map help you determine whether an air mass is dry or humid?

8.4 Air-Mass Modification

LO 4 Describe the processes by which traveling air masses are modified and discuss two examples.

The previous section describes how an air mass influences weather as it moves. Once an air mass moves from its source region, it not only modifies the weather of the area it is traversing, but also is gradually modified by the surface over which it moves. This idea is illustrated in Figure 8.2. Warming or cooling from below, the addition or loss of moisture, and vertical air movements all act to change an air mass.

Warming or Cooling an Air Mass

An air mass that is colder than the surface it passes over will be warmed from below. This fact causes greater instability that favors the ascent of the heated lower layers, which contributes to cloud formation and possibly precipitation. Air masses modified by surface heating often exhibit cumulus or cumulonimbus clouds, and if precipitation occurs, it generally consists of showers or thunderstorms.

> When an air mass moves over a surface with different properties, the air mass not only modifies the area it is traversing, but also is gradually modified by the surface over which it moves.

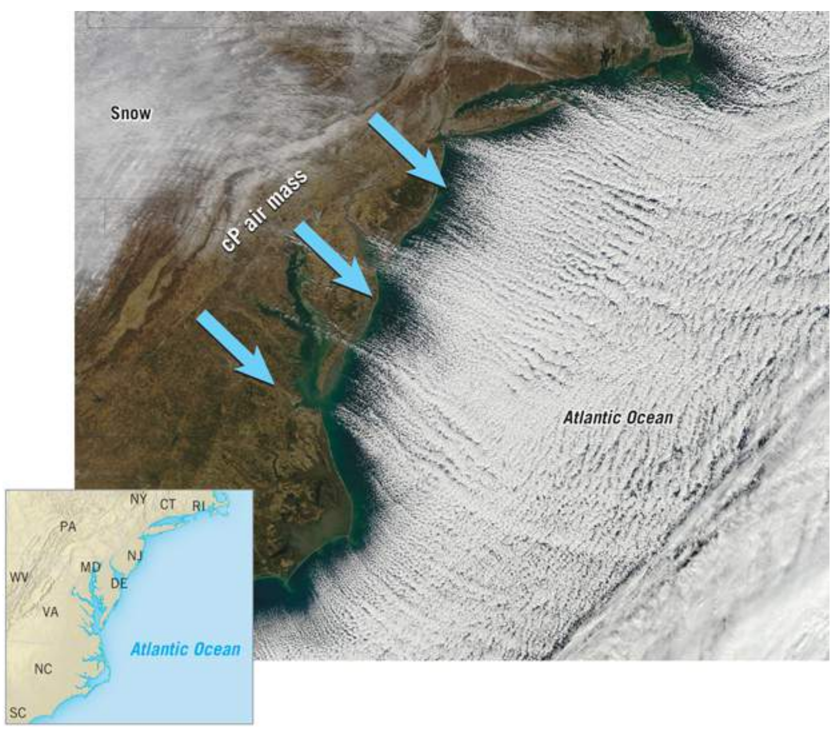
Conversely, when an air mass is warmer than the surface over which it is moving, its lower layers are chilled. An inversion caused by cooler air near the surface and warmer air aloft increases the stability of the air mass—a condition that inhibits the ascent of air. Thus, cooling air from below limits the potential for cloud formation and precipitation. Any clouds that form are stratus clouds, and precipitation, if any, is light to moderate. Moreover, because of the lack of vertical movements, smoke and dust often become concentrated in the lower layers of the air mass and cause poor visibility. During certain times of the year, fogs, especially advection fog (see Chapter 5), are common in regions that have been invaded by a warm air mass moving across a cool surface, such as a cold ocean current.

Addition or Loss of Moisture

When a dry, cold (cA or cP) air mass moves over a large expanse of the ocean in winter, it is greatly modified (Figure 8.13). Evaporation from the water surface rapidly transfers large quantities of moisture to the once-dry continental air. Furthermore, because the underlying water is warmer than the air above, the air is also heated from below. These factors lead to instability and vertically ascending currents that rapidly transport heat and moisture to higher levels (see Figure 8.5). In a relatively short time span, a cold, dry, and stable continental air mass is transformed into an unstable mP air mass.*

Figure 8.13 Air-mass modification

This satellite image from January 7, 2014, shows the modification of cold, dry, and cloud-free cP air that produced a cold snap in the eastern United States. As the air mass moved over the Atlantic, the addition of heat and water vapor from the relatively warm water quickly modified the air mass and created instability, as evidenced by the development of clouds.



Vertical Motion and Stability

Upward and downward movements induced by cyclones, anticyclones, or topography can also affect the characteristics and stability of an air mass. Such modifications are usually independent of the changes caused by surface cooling or heating. For example, significant modification can result when an air mass is drawn into a surface low-pressure system (cyclone). Here convergence and lifting dominate, which can result in instability. Conversely, the subsidence associated with anticyclones acts to stabilize an air mass. Similar changes in stability occur when an air mass is lifted over highlands or descends the leeward side of a mountain barrier. In the first case, the air's instability is enhanced; in the second case, the air becomes more stable.

> Air masses are modified by warming or cooling from below, the addition or loss of moisture, and vertical air movements.

Recall that a moist, cool mP air mass originating over the Pacific is modified as moves onshore and is lifted over a mountain range, such as the Sierra Nevada. On the windward slope, the moist air mass cools and forms clouds that frequently produce precipitation. As this air descends the leeward side of the mountain, it is heated adiabatically, resulting in a dryer and warmer air mass that has the characteristic of a continental air mass—dry and warm rather than cool and moist.

Lake-Effect Snow: Cold Air over Warm Water

A glance at the chapter-opening image provides an atmospheric perspective of the conditions that produce what is called **lake-effect snow**. The skies over Lake Superior and Lake Michigan exhibit long rows of dense, white, snow-producing clouds. They formed within a cold, dry cP air mass that was modified as it moved from land across open water. Continental polar air masses are not, as a rule, associated with dense clouds and heavy precipitation. Yet during late autumn and winter, this unique weather phenomenon occurs along the downwind shores of the five Great Lakes—as long as the lake is not frozen over. The stability and moisture content of the cP air mass is modified as it travels and, in turn, influences the weather as it continues to move.

These highly localized storms can produce heavy snow showers as the dark clouds move onshore (Figure 8.14). Seldom do these storms move more than about 80 kilometers (50 miles) from the lakeshore before the snows come to an end. Although lake-effect snow is associated primarily with the Great Lakes, other large lakes can experience this phenomenon as well.

Figure 8.14 State snowfall record

A 6-day lake-effect snowstorm in November 1996 dropped 175 centimeters (nearly 69 inches) of snow on Chardon, Ohio, setting a new state record.

> Lake-effect snow forms when cold cP air moves over the comparatively warm water of a large lake.

What causes lake-effect snow? The answer is closely linked to the differential heating of water and land. During the summer months, bodies of water such as the Great Lakes absorb huge quantities of energy from the Sun and from the warm air that passes over them. Although these water bodies do not reach particularly high temperatures, they nevertheless represent huge reservoirs of heat. The surrounding land, in contrast, cannot store heat nearly as effectively. Consequently, during autumn and winter, the temperature of the land drops quickly, whereas water bodies lose their heat more gradually and cool slowly.

Lake-effect storms account for a high percentage of the snowfall in many areas adjacent to the Great Lakes. The areas most frequently affected, called *snowbelts*, are shown in Figure 8.15. A comparison of average snowfall totals at Thunder Bay, Ontario, on the northern shore of Lake Superior, and Marquette, Michigan, along the southern shore, provides an excellent example. Because Marquette is situated on the leeward shore of the lake, it receives substantial lake-effect snow and therefore has a much higher snowfall total than does Thunder Bay (Table 8.2).

Figure 8.15 Snowbelts of the Great Lakes region

Table 8.2 Monthly Snowfall at Thunder Bay, Ontario, and Marquette, Michigan

Thunder Bay, Ontario			
October	**November**	**December**	**January**
3.0 cm (1.2 in.)	14.9 cm (5.8 in.)	19.0 cm (7.4 in.)	22.6 cm (8.8 in.)
Marquette, Michigan			
October	**November**	**December**	**January**
5.3 cm (2.1 in.)	37.6 cm (14.7 in.)	56.4 cm (22.0 in.)	53.1 cm (20.7 in.)

Eye on the Atmosphere 8.2

An intense cold snap in early January 2014 brought thick and widespread ice to the Great Lakes. This satellite image from January 9 shows Lake Erie 90 percent ice covered.

NOAA

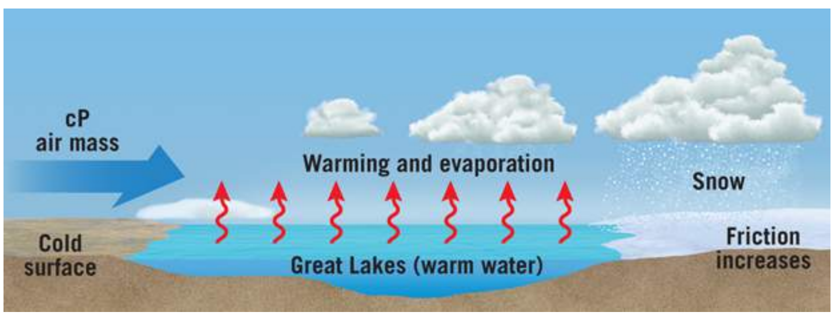
Apply What You Know

1. When compared to an ice-free condition, would the situation depicted here promote more lake-effect snowstorms, reduce the chances of lake-effect snow, or likely have no effect?
2. Explain the reasoning you used to answer Question 1.

From late November through late January, the contrasts in average temperatures between water and land range from about 8°C in the southern Great Lakes to 17°C farther north. However, the temperature differences can be much greater (perhaps 25°C) when a very cold cP or cA air mass pushes southward across the lakes. When such a dramatic temperature contrast exists, the lakes interact with the air to produce major lake-effect storms. Figure 8.16 depicts the movement of a cP air mass across one of the Great Lakes. During its journey, the air acquires large quantities of heat and moisture from the relatively warm lake surface. A greater fetch (distance across the open water) leads to a greater modification of the air mass. At the opposite shore, the leading edge of the air mass slows down because of the increased friction over the land. This causes convergence and lifting of the humid, unstable air, resulting in heavy snow showers.

Figure 8.16 Lake-effect snow

When continental polar air crosses the Great Lakes in winter, it acquires moisture and becomes unstable because of warming from below. Lake-effect snow showers on the downwind side of the lakes often result from this air-mass modification.



You might have wondered . . .

I know that Buffalo, New York, is famous for its lake-effect snows. Just how bad can it get?

Located along Lake Erie's eastern shore, Buffalo does indeed receive a great deal of lake-effect snow (see Figure 8.15). Between December 24, 2001, and January 1, 2002, Buffalo's longest-lasting lake-effect event buried the city under 207.3 centimeters (81.6 inches) of snow. Prior to this storm, the record for the entire month of December had been 173.7 centimeters (68.4 inches)! The eastern shore of Lake Ontario was also hard hit, with one station recording more than 317 centimeters (125 inches) of snow.

Concept Checks 8.4

- How might vertical movements induced by a pressure system or topography act to modify an air mass?
- Describe the modifications that occur as a cP air mass passes across a large ice-free lake in winter.

*When an air mass is colder than the surface over which it is passing, the lowercase letter k is added after the air-mass symbol. If, however, an air mass is warmer than the underlying surface, the lowercase letter w is added. The k or w designation gives an indication of the stability of an air mass and, hence, the weather that might be expected.

Concepts in Review

8.1 What Is an Air Mass?

LO 1 Define *air mass* and *air-mass weather*.

Key Terms

air mass

air-mass weather

- An air mass is a large body of air, usually 1600 kilometers (1000 miles) or more across, that is characterized by similar temperature and moisture conditions at any given height.
- A region under the influence of an air mass usually exhibits relatively uniform weather conditions perhaps for several days, a situation referred to as air-mass weather.

8.2 Classifying Air Masses

LO 2 List the basic criteria for an air-mass source region and identify the source regions that influence North America.

Key Terms

source region

polar (P) air mass

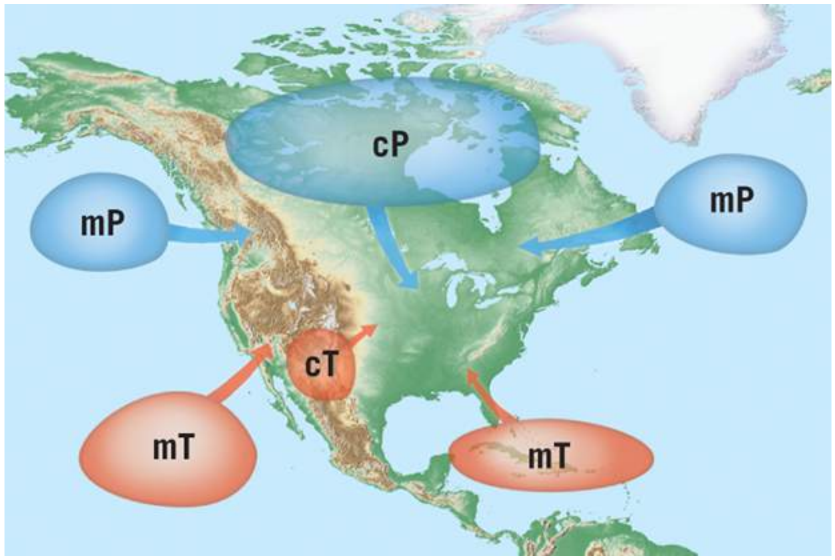
arctic (A) air mass

tropical (T) air mass

maritime (m) air mass

continental (c) air mass

- Areas in which air masses originate, called source regions, must be extensive and physically uniform and must be characterized by a general stagnation of atmospheric circulation.
- The classification of an air mass depends on the latitude of the source region and the nature of the surface in the area of origin—ocean or continent. Air masses are identified by two-letter codes. Continental (c) designates an air mass of land origin, with the air likely to be dry, whereas a maritime (m) air mass originates over water and therefore is humid. Polar (P) and arctic (A) air masses originate in high latitudes and are cold. Tropical (T) air masses form in low latitudes and are warm.
- According to this classification scheme, the basic types of air masses are continental polar (cP), continental arctic (cA), continental tropical (cT), maritime polar (mP), and maritime tropical (mT).


cP
mP
mP
cT
mT
mT

8.3 Properties of North American Air Masses

LO 3 Summarize the weather conditions associated with the air masses that influence North America during the summer and winter.

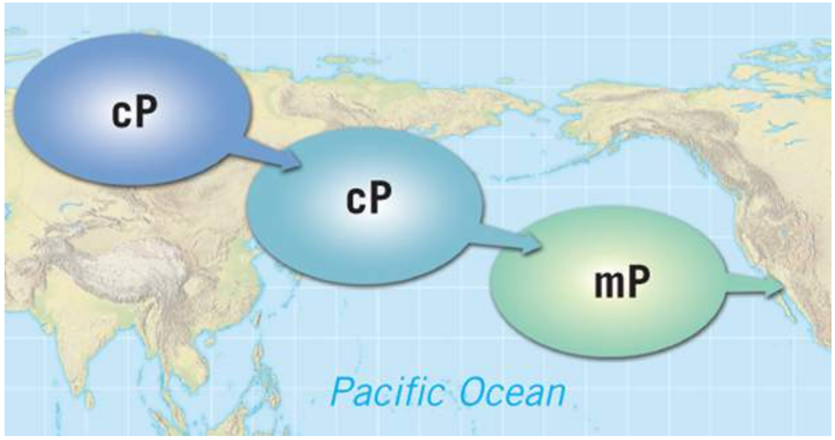
Key Terms

nor’easter

isohyet

atmospheric river

- Continental polar (cP) and maritime tropical (mT) air masses primarily influence the weather of North America, especially east of the Rocky Mountains, because the convergence associated with traveling cyclones draws these contrasting air masses together.
- Maritime polar (mP) air masses that influence the Pacific coast of North America tend to be unstable in winter and stable in summer. Storms called nor’easters result when mP air from the North Atlantic is drawn into a low-pressure center along the east coast.
- Maritime tropical (mT) air masses from the Gulf of Mexico and adjacent Atlantic Ocean are a major source of precipitation in the eastern two-thirds of the United States.
- Pacific mT air masses affect North America much less than mT air masses from the Gulf of Mexico and the adjacent North Atlantic. Sometimes mT air from the subtropical Pacific is part of an atmospheric river, a narrow corridor of concentrated moisture that can produce heavy rains along the Pacific coast.


cP
cP
mP
Pacific Ocean

8.4 Air-Mass Modification

LO 4 Describe the processes by which traveling air masses are modified and discuss two examples.

Key Term

lake-effect snow

- Changes to the stability of an air mass can result from temperature differences between an air mass and the surface and/or vertical movements induced by cyclones, anticyclones, or topography.
- An air mass that is colder than the surface beneath it tends to become unstable. An air mass that is chilled from below tends to become stable.
- Convergence and lifting cause an air mass to become more unstable, whereas subsidence acts to stabilize an air mass.
- Lake-effect snows occur on the downwind sides of large lakes and are associated with cP air masses that move across comparatively warm lakes, where they are supplied with moisture and become unstable.

Exercises and Online Activities

Mastering Meteorology™
For instructor-assigned homework, test prep resources, and other learning materials, visit **Mastering Meteorology.**

Review Questions

1. Explain how air masses form.
2. Define *source region*.
3. How are air masses classified?
4. Where do the following air masses originate: mP; cP; mT; cT; and cA?
5. Describe the characteristics of the air masses listed in Question 4.
6. What is an atmospheric river?
7. List and describe three ways in which air masses get modified.
8. What is lake-effect snow, and how does it form?

Give It Some Thought

1. Air-mass source regions are large, relatively homogenous areas. As the accompanying map illustrates, the broad expanse between the Appalachians and the Rockies is such a zone, yet air masses do not form here. Why is this area not a source region?

2. Air masses can be classified as cold or warm, but there is variation within this designation. In each case that follows, provide a brief explanation for your answer.
    a. We know that during the winter, all polar (P) air masses are cold. Which should be colder: a wintertime mP air mass or a wintertime cP air mass?
    b. We expect tropical (T) air masses to be warm, but some are warmer than others. Which should be warmer: a summertime cT air mass or a summertime mT air mass?
3. What is the proper classification for an air mass that forms over the Arctic Ocean in winter: cA or mA? Explain your choice.

4. The Great Lakes are not the only water bodies associated with lake-effect snow. For example, large lakes in Canada also experience this phenomenon. Shown below are snowfall data for Fort Resolution, a settlement on the southeastern shore of Great Slave Lake.

During what month is snowfall greatest? Suggest an explanation as to why the maximum occurs when it does.

5. In each of the situations described here, indicate whether the air mass is becoming more stable or more unstable. Briefly explain each choice.

  a. An mT air mass moving northward from the Gulf of Mexico over the southeastern states in winter

  b. A cP air mass moving southward across Lake Superior in late November

  c. An mP air mass in the North Atlantic drawn into a low-pressure center off the coast of New England in January

  d. A wintertime cP air mass from Siberia moving eastward from Asia across the North Pacific

6. Refer to Figure 8.15. Notice the narrow, north–south oriented zone of relatively heavy snowfall east of Pittsburgh, Pennsylvania, and Charleston, South Carolina. This region is too far from the Great Lakes to receive lake-effect snows. Speculate on a likely reason for the higher snowfalls here. Does your explanation explain the shape of this snowy zone?

By the Numbers

1. Albuquerque, New Mexico, is situated in the arid U.S. Southwest. Its annual precipitation is just 21.2 centimeters (8.3 inches). Monthly data (in centimeters) are as follows:

Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
1.0	1.0	1.3	1.3	1.3	1.3	3.3	3.8	2.3	2.3	1.0	1.3

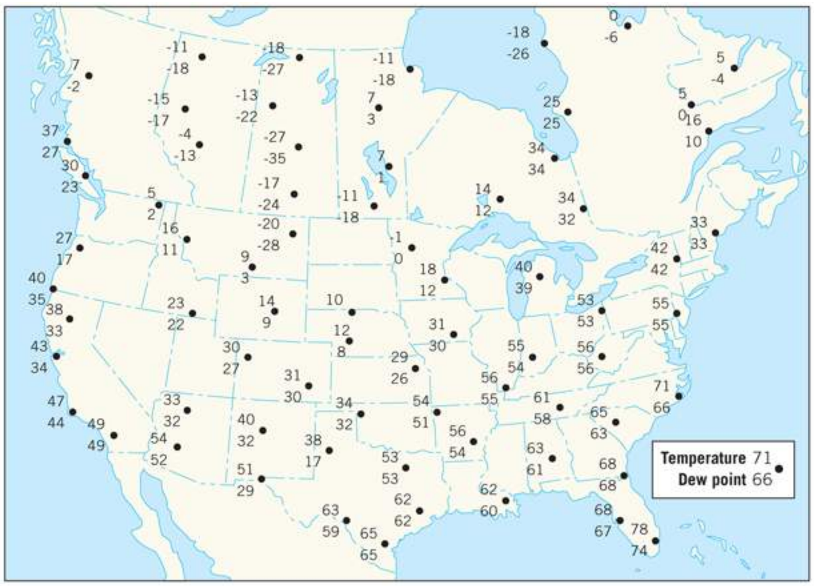
What are the two rainiest months for Albuquerque? The pattern here is similar to the pattern in other southwestern cities, including Tucson, Arizona. Briefly explain why the rainiest months occur when they do.

Beyond the Textbook

Recall that air masses are identified by there temperature and moisture content. Air temperature is usually plotted on weather maps, but humidity is often determined by comparing the air's temperature to its dew-point temperature. The closer the dew-point temperature is to the air temperature, the more humid the air mass. When these measures are the same, the air is saturated, and the relative humidity is 100 percent. Using this information, complete the following activities.

1. Using Station Model Data

The accompanying map shows the distribution of air temperatures (top number) and dew-point temperatures (lower number) for a December morning. Two well-developed air masses are influencing North America at this time. The air masses are separated by a broad zone that is not affected by either air mass.



Air temperatures and dew-point temperatures in Fahrenheit for weather stations on a December morning.

1. Use temperature and dew point data to draw two lines on the map to show the boundaries of each air mass.
2. Describe the temperature and humidity of each air mass.
3. Label each air mass with its proper classification.

2. Using Contour Maps

Go to https://www.atmos.illinois.edu/weather/ and find the Surface Temperature and Surface Dew Point Temperature maps. Click on these maps to examine a larger version of each. Keep in mind the season and the air masses that generally impact the weather in the United States to complete the following:

1. Look for regions with uniform temperatures and dew-point temperatures that appear to be air masses.
2. Based on air temperature and dew-point temperature data, classify each of the air masses you located.
3. Give a brief description of the locations of each air mass.

Click the Archive tab at the bottom of the Surface Temperature map, and then click on month (M). Next select the January map, then the January 15 map, and finally the 12Z map (which is early morning in the eastern United States).

4. Based solely on temperature, classify each air mass depicted on this map.
5. Give a brief description of the location of each air mass.

Again click on the word Archive at the bottom of the Surface Temperature map, and then click on month. Next select the July map, then the July 15 map, and finally the 17Z map (which is noon eastern standard time). Repeat these steps for the Dew Point Temperature map, and compare the two maps.

6. Based on air temperature and dew-point temperatures, find a location that is hot and dry. Describe this region geographically, and classify this air mass.

7. Based on air and dew-point temperatures, find a location that is hot and humid. Describe this region geographically, and classify this air mass.

Chapter 9 Midlatitude Cyclones

Supercell moves across country near West Point, Nebraska.

Focus on Concepts

Each statement represents the primary learning objective for the corresponding major heading within the chapter. After you complete the chapter, you should be able to:

1. Compare and contrast typical weather associated with a warm front, cold front, occluded front, stationary front, and dryline (9.1).
2. Outline the stages in the life cycle of a typical midlatitude cyclone (9.2).
3. Relate divergence in airflow aloft to the development and intensification of a midlatitude cyclone at the surface (9.3).
4. Explain the conveyor belt model of a midlatitude cyclone and describe the three interacting air streams on which it is based (9.4).
5. Identify on a map the primary sites for the development of midlatitude cyclones affecting North America. Indicate typical paths for Alberta clippers, Colorado lows, Panhandle lows, Gulf lows, and nor'easters (9.5).
6. Describe the general weather conditions associated with the passage of a mature midlatitude cyclone (9.6).
7. Define a blocking high-pressure system and explain how it influences weather over the midlatitudes (9.7).
8. Summarize the weather associated with a midlatitude cyclone over the north-central United States in winter (9.8).

The winter of 1992–1993 came to a stormy conclusion in eastern North America one weekend in March. Daffodils were blooming across the South, and people were thinking about spring when the blizzard of ’93 struck on March 13 and 14. The huge storm brought record-low temperatures and barometric pressure readings, accompanied by record-high snowfalls from Alabama to the Maritime Provinces of eastern Canada. The monster storm, with its driving winds and heavy snow, combined the attributes of a hurricane and a blizzard as it moved up the spine of the Appalachians, lashing and burying a huge swath of territory. Although the atmospheric pressure at the storm’s center was lower than the pressures at the centers of some hurricanes and the winds were frequently as strong as those in hurricanes, this was not a tropical storm—but instead a classic winter cyclone.

9.1 Frontal Weather

LO 1   Compare and contrast typical weather associated with a warm front, cold front, occluded front, stationary front, and dryline.

In previous chapters, we examined the basic elements of weather as well as the dynamics of atmospheric motions. Our knowledge of these diverse phenomena applies directly to an understanding of day-to-day weather patterns in the middle latitudes. For our purposes, *middle latitudes* refer to the area of North America roughly between southern Alaska and Florida — essentially the area of the prevailing westerlies, where the primary weather producer is the *midlatitude*, or *middle-latitude*, *cyclone*. Midlatitude cyclones go by several different names, including *wave cyclones*, *frontal cyclones*, *extratropical cyclones*, *low-pressure systems*, and, simply, *lows*.

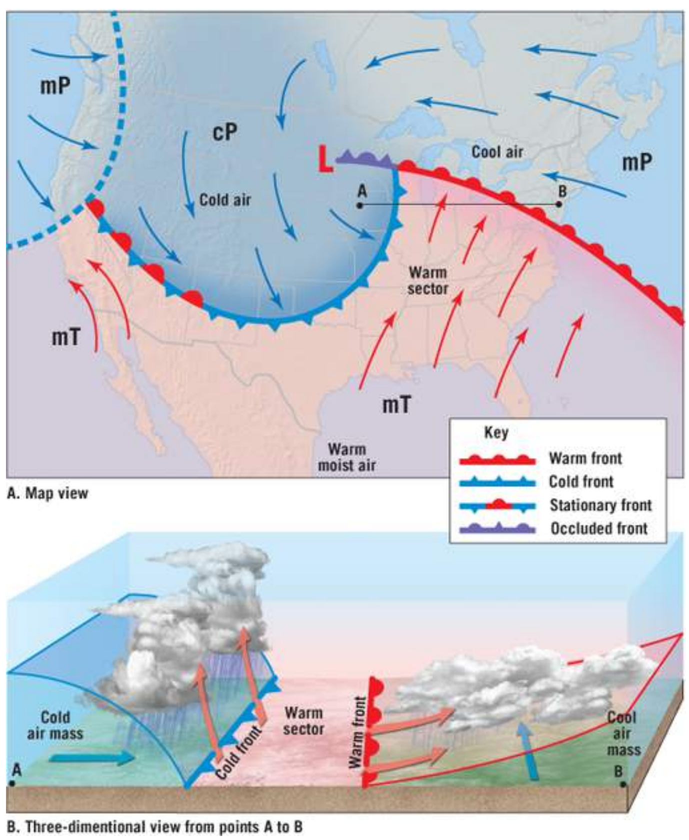
Because *weather fronts* are the major weather producers imbedded within midlatitude cyclones, we will begin our discussion with these basic structures.

What Is a Front?

One prominent feature of middle-latitude weather is how suddenly and dramatically it can change (see the chapter-opening photo). Most of these sudden changes are associated with the passage of weather fronts. A **front** is a boundary surface that separates air masses of different densities—one of which is usually warmer and contains more moisture than the other. However, fronts can form between any two contrasting air masses. When the vast sizes of air masses are considered, the fronts that separate them are relatively narrow and are shown as lines on weather maps (Figure 9.1).

Figure 9.1 Idealized structure of a midlatitude cyclone

A. Map view showing fronts, air masses, and surface winds. **B.** Three-dimensional view of the warm and cold fronts along a line from point A to point B.



> A front is a boundary between two air masses—one of which is usually warmer and contains more moisture than the other.

Generally, the air mass located on one side of a front moves faster than the air mass on the other side. Thus, one air mass actively advances into the region occupied by another and collides with it. During World War I, Norwegian meteorologists visualized these zones of air-mass interactions as analogous to battle lines and tagged them "fronts," as in battlefronts. It is along these zones of "conflict" that midlatitude cyclones produce much of the precipitation and severe weather in the belt of the westerlies.

As one air mass moves into a region occupied by another, minimal mixing occurs along the frontal surface. Instead, the air masses retain their identity as one is displaced upward over the other. No matter which air mass is advancing, it is always the warmer, less dense air that is forced aloft, whereas the cooler, denser air acts as a wedge on which lifting occurs. The process of warm air gliding up and over a cold air mass is termed **overrunning**.

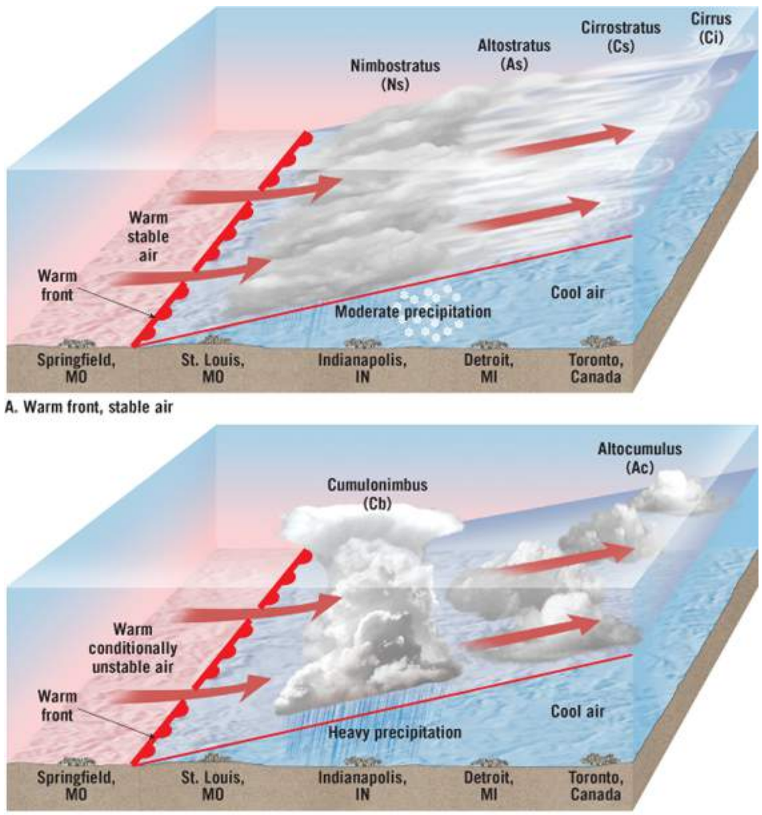
There are five basic types of fronts—*warm fronts*, *cold fronts*, *stationary fronts*, *occluded fronts*, and *drylines*. Each type of front separates air masses of different densities, which is due to the temperature and/or humidity differences that exist on opposite sides of the front.

Warm Fronts

When the surface position of a front moves so that warmer air invades territory formerly occupied by cooler air, it is called a **warm front** (Figure 9.2). On a weather map, a warm front is shown as a red line with red semicircles protruding into the area of cooler air. East of the Rockies, warm fronts are usually associated with maritime tropical (mT) air that enters the United States from the Gulf of Mexico and “glides” over cooler air positioned over land. The boundaries separating these air masses have very gradual slopes that average about 1:200 (height compared to horizontal distance). This means that if you traveled 200 kilometers (120 miles) ahead of the surface location of a warm front, the frontal surface would be 1 kilometer (0.6 mile) overhead.

Figure 9.2 **Warm fronts**

A. Idealized clouds and weather associated with a warm front. During winter and early spring, warm fronts produce light to moderate precipitation, often consisting of snow, sleet, and rain, over a wide area. **B.** During the warm season, when conditionally unstable air is forced aloft, cumulonimbus clouds (thunderstorms) often arise.



A. Warm front, stable air

B. Warm front, conditionally unstable air

Watch Animation: Warm Fronts

As warm air ascends over the retreating wedge of cold air, it expands and cools adiabatically. As a result, moisture in the ascending air condenses to generate clouds that may produce precipitation. The cloud sequence in Figure 9.2A typically *precedes* the approach of a warm front. The first sign of the approaching warm front is cirrus clouds that form 1000 kilometers (600 miles) or more ahead of the surface front. Aircraft contrails provide another clue that a warm front is approaching. On a clear day, when condensation trails persist for several hours, you can be fairly certain that comparatively warm, moist air is ascending overhead.

As the front nears, cirrus clouds grade into cirrostratus that gradually blend into denser sheets of altostratus. About 300 kilometers (180 miles) ahead of the front, thicker stratus and nimbostratus clouds that generate precipitation begin to form.

> Prior to the arrival of a warm front, winds tend to be from the east, temperatures are cool, and cloud cover gradually thickens.

Because warm fronts have relatively gentle slopes, the cloud deck that results from frontal lifting covers a large area and produces an extended period of light to moderate precipitation. However, if the overriding air mass is relatively dry (low dew-point temperatures), there is minimal cloud development and no precipitation. By contrast, during the spring and early summer when moist, conditionally unstable air is often forced aloft, towering cumulonimbus clouds and thunderstorms may occur (Figure 9.2B).

As you can see from Figure 9.2A, the precipitation associated with a warm front occurs ahead of its surface position. Therefore, any precipitation that forms must fall through the cool layer below. During extended periods of light rainfall, enough of these raindrops may evaporate for saturation to occur, resulting in the development of a low-level stratus cloud deck. These clouds occasionally thicken, causing problems for pilots of small aircraft who rely solely on visual landings. In these situations, aircraft pilots may enter a cloud mass at or near the ground, called *frontal fog*, that has the landing strip "socked in."

> After a warm front has passed, winds are from the south, temperatures warm, and the sky gradually clears.

In winter, snow may replace rain as the dominant form of precipitation associated with a warm front. In addition, when a relatively warm air mass is forced over a body of subfreezing air, hazardous driving conditions may occur ahead of a warm front. The raindrops may become supercooled as they fall through the subfreezing air and freeze on contact with road surfaces to produce an icy layer called *freezing rain*. Alternatively, the raindrops freeze as they pass though the layer of cold air and fall as ice pellets called *sleet* (see Figure 5.20,).

Temperatures gradually rise as the warm front passes. As you would expect, the increase is most apparent when a large contrast exists between adjacent air masses. Moreover, easterly winds are replaced by southwesterly flow. The moisture content and stability of the encroaching warm air mass largely determine the time required for clear skies to return. During the summer, cumulus and occasionally cumulonimbus clouds are embedded in the warm, humid, and unstable air mass that follows the front. These clouds may produce precipitation, which can be heavy but is usually scattered and of short duration. Table 9.1 shows the typical weather conditions that can be expected with the passage of a warm front in the Northern Hemisphere.

Table 9.1 Weather Typically Associated with a Warm Front (North America)

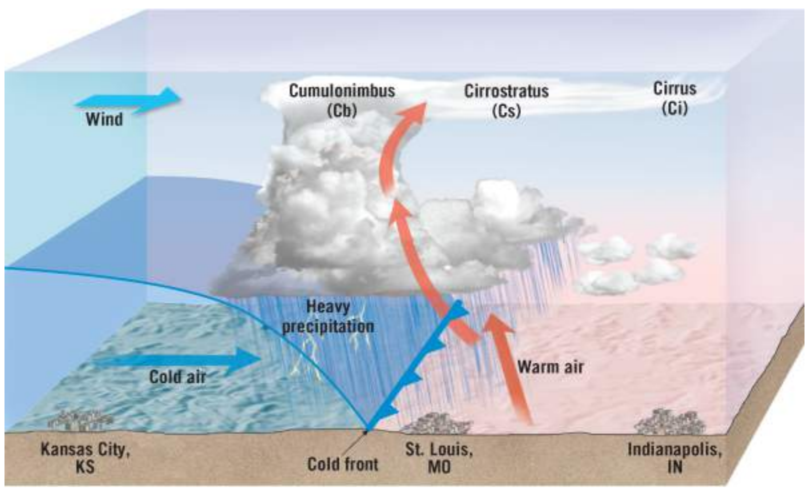
Weather Element	Before Passage	During Passage	After Passage
Temperature	Cool or cold	Rising	Warmer
Winds	East or southeast	Variable	South or southwest
Clouds	Cirrus, cirrostratus, stratus, nimbostratus when air is stable; cumulonimbus when air is conditionally unstable	None, stratus, or fog	Clearing, cumulus, or cumulonimbus in summer
Precipitation	Light to moderate rain, snow, or freezing rain in winter; heavy rain possible in summer	None or light rain	None, occasionally showers in summer
Pressure	Falling	Falling or steady	Rising
Humidity	Moderate to high	Rising	High, particularly in summer

Cold Fronts

When cold air advances into a region occupied by warmer air, the zone of discontinuity is called a **cold front** (Figure 9.3). On a weather map, a cold front is shown as a blue line with blue triangles protruding into the area of warmer air. Because of surface friction, the cold air near the ground advances more slowly than the air aloft. As a result, cold fronts steepen as they move.

SmartFigure 9.3 **Fast-moving cold front with cumulonimbus clouds**

Thunderstorms often occur if the warm air is unstable.



Watch **SmartFigure: Fronts**

Cold fronts are typically twice as steep as warm fronts, having slopes of perhaps 1:100. In addition, cold fronts advance at speeds up to 80 kilometers (50 miles) per hour, about 50 percent faster than warm fronts. These two differences—steepness of slope and rate of movement—largely account for the nature of cold-front weather, which tends to be more violent compared to warm-front weather.

Cold fronts generally approach from the west or northwest, indicated by a band of ominous clouds foretelling the ensuing weather. The forceful lifting of warm, moist air along a cold front is often rapid enough that the released latent heat increases the air's buoyancy sufficiently to render the air unstable. Heavy downpours and vigorous wind gusts associated with mature cumulonimbus clouds frequently result. Because a cold front produces roughly the same amount of lifting as a warm front, but over a shorter distance, the precipitation is generally more intense but of shorter duration. A marked temperature drop and wind shift from the southwest to the northwest usually accompanies the passage of a cold front.

> Prior to the arrival of a cold front, an area experiences an increase in winds from a southerly direction and warm temperatures, while a line of thunderstorms may be visible in the distance.

The weather following the passage of a cold front is dominated by subsiding air within a continental polar (cP) air mass. Although subsidence causes adiabatic heating aloft, the effect on surface temperatures is offset by cold air advection. Thus, the temperature drops and the skies begin to clear soon after the front passes. In winter, the long, cloudless nights that follow the passage of a cold front allow for abundant radiation cooling, which produces frigid surface temperatures. By contrast, a passing cold front during a summer heat wave produces a welcome change in conditions as hot, hazy mT air is replaced by cool, clear cP air.

When the air behind a cold front traverses a relatively warm surface, radiation emitted from Earth's surface can heat the air enough to produce shallow convection. This in turn may generate low cumulus or stratocumulus clouds behind the front. However, subsidence aloft keeps these air masses relatively stable. Any clouds that form will not develop great vertical thickness and will seldom produce precipitation. One exception is the lake-effect snow discussed in Chapter 8, in which the cold air behind a front acquires heat and moisture as it traverses a comparatively warm body of water.

> After the passage of a cold front, winds are out of the northwest, temperatures decrease, and skies clear.

Eye on the Atmosphere 9.1

The accompanying five images show clouds that commonly form along frontal boundaries. Four of these cloud types are produced when stable air ascends a warm frontal boundary, and the other tends to form along a cold front.

Apply What You Know

1. Which one of these five cloud types (A–E) tends to be generated along a cold front?
2. If a warm front is approaching your location, list the names and appropriate letters of the other four clouds in the order in which they would pass overhead.

In North America, cold fronts form most commonly when a cP air mass clashes with maritime tropical (mT) air. However, wintertime cold fronts can form when even colder, dryer continental arctic (cA) air invades a continental polar (cP) or maritime polar (mP) air mass. Over land, arctic cold fronts tend to produce very light snow because the cP air masses they invade are quite dry. By contrast, an arctic cold front passing over a relatively warm water body may yield heavy snowfall and gusty winds. Table 9.2 shows the typical weather conditions associated with the passage of a cold front in North America.

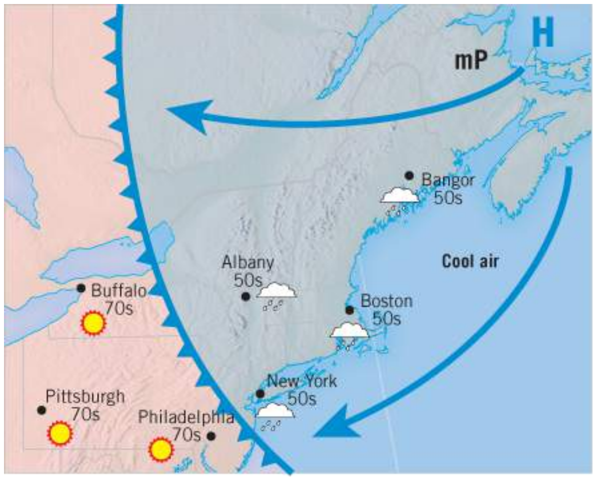
Table 9.2 Weather Typically Associated with a Cold Front (North America)

Weather Element	Before Passage	During Passage	After Passage
Temperature	Warm	Sharply dropping	Colder
Winds	South or southwest	Variable and gusty	West or northwest
Clouds	None, cumulus, or cumulonimbus	Cumulonimbus	None or cumulus in summer
Precipitation	None or showers	Thunderstorms in summer, rain or snow in winter	Clearing
Pressure	Falling	Falling then rising	Rising
Humidity	High, particularly in summer	Dropping	Low, particularly in winter

A type of cold front termed a **backdoor cold front** sometimes affects the eastern seaboard of North America. Most cold fronts arrive from the west or northwest, whereas backdoor cold fronts come in from the northeast, hence their name. Driven by clockwise circulation from a strong high-pressure center over northeastern Canada, colder, denser maritime polar (mP) air from the North Atlantic displaces warmer, lighter air over the continent, as shown in Figure 9.4. Backdoor fronts are primarily springtime events that tend to bring cold temperatures, low clouds, and drizzle, although thunderstorms occasionally occur.

Figure 9.4 Weather associated with a backdoor cold front in the Northeast

In early spring, a warm, sunny day can become chilly and damp as cool, moist maritime polar (mP) air moves inland from the North Atlantic.



Watch Animation: Cold Fronts

Stationary Fronts

Occasionally, airflow on both sides of a front is neither toward the cold air mass nor toward the warm air mass. Rather, it is almost parallel to the line of the front. Consequently, the surface position of the front does not move, or it moves sluggishly. This condition is called a **stationary front**. On a weather map, a stationary front is shown with blue triangles pointing into the warm air and red semicircles pointing into the cold air (see Figure 9.1A). Because some overrunning usually occurs along stationary fronts, gentle to moderate precipitation is likely. Stationary fronts may remain over an area for several days, in which case ongoing rainfall may result in flooding. When stationary fronts begin to move, they become cold or warm fronts, depending on which air mass advances.

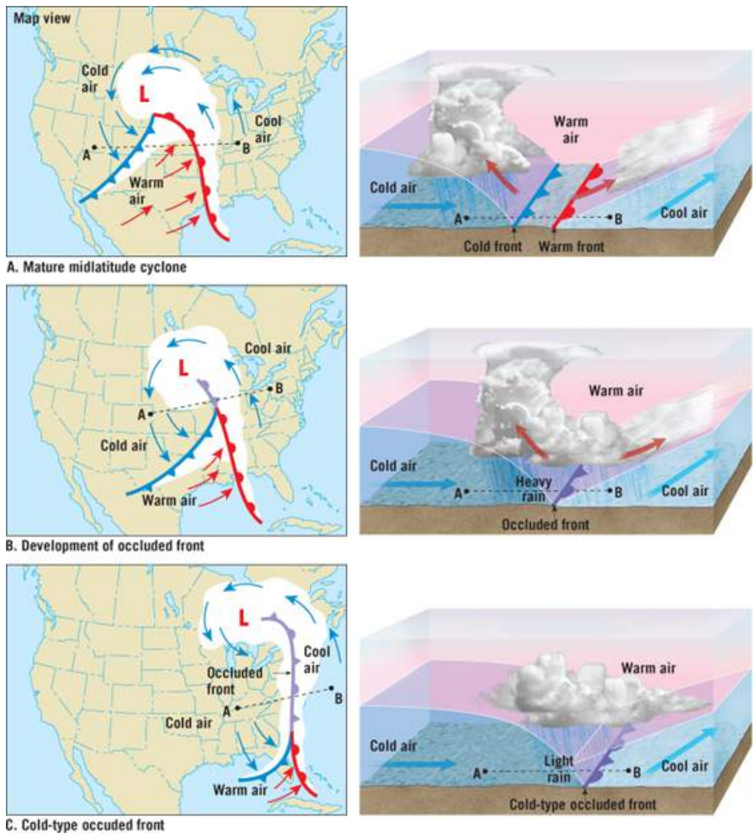
> A stationary front separates warm air on one side and cold on the other, while its position remains relatively fixed.

Occluded Fronts

An **occluded front** most often forms when a rapidly moving cold front overtakes a warm front, as shown in Figure 9.5. Occluded (meaning concealed or hidden) fronts are named for the warm air that is lifted above the ground and "hidden" by colder air below. As the cold front forces the warm front aloft, a new front forms between the advancing cold air and the cool air over which the warm air is gliding. This process, known as **occlusion**, occurs in the later stages of the storm's life cycle. Occlusion, therefore, produces two fronts—one at the surface and one aloft.

Figure 9.5 Stages in the formation of a cold-type occluded front

A. Mature midlatitude cyclone with warm and cold fronts. **B.** The cold front overtakes the warm front to produce a cold-type occluded front. **C.** After the warm air has been forced aloft, the system begins to dissipate. The areas shown in white on the map indicate regions where clouds and precipitation are most likely to occur.



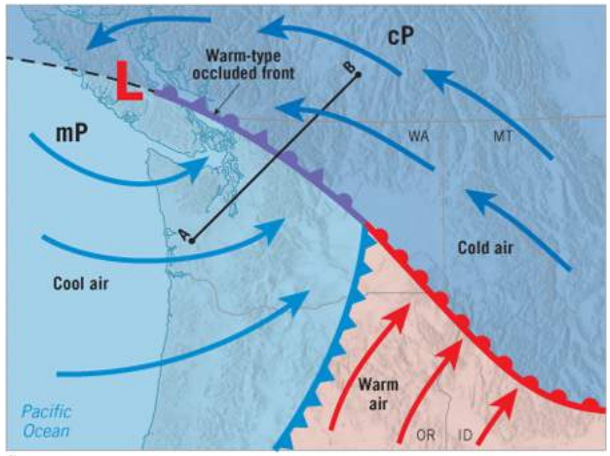
Occluded fronts are drawn on weather maps as a purple line with alternating purple triangles and semicircles pointing in the direction of movement. There are cold-type occluded fronts and warm-type occluded fronts. In a **cold-type occluded front**, like the one shown in Figure 9.5, the cold front lifts both the warm front as well as the cool air mass that lies ahead of it. Initially, the weather is like that associated with a warm front. However, as the occlusion develops and the warm air is lifted increasingly higher, thunderstorms may develop, mainly in the summer. By contrast, in winter the affected region may experience blizzard conditions. Thus, fully developed cold-type occluded fronts often resemble cold fronts in the type of weather generated.

> A cold-type occluded front occurs when a cold front overtakes a warm front, lifting the warm air off the ground.

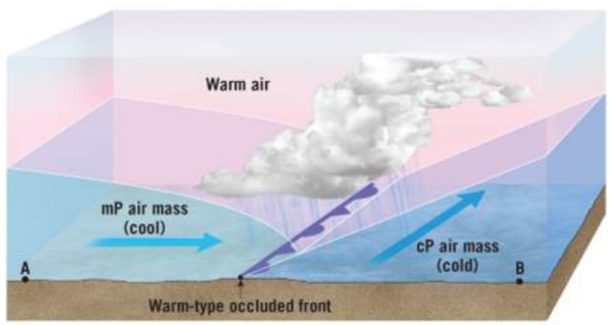
A **warm-type occluded front** develops when the air behind an advancing occluded front is warmer than the air ahead of the front. This type of occluded front often forms along the west coast of continents, where milder maritime polar air invades frigid polar air that originated over the adjacent continent (Figure 9.6). In this situation, the cool air is warmer and lighter than the cold air ahead of the front. Consequently, the cool air ascends and moves over the denser cold air ahead of the newly formed occluded front. The weather associated with a warm-type occlusion is usually like that of a warm front: gentle to moderate precipitation. However, if the warm air that is lifted is conditionally unstable, thunderstorms can develop.

Figure 9.6 **Warm-type occluded front**

A. Map showing the location of a warm-type occluded front in relationship to maritime polar (mP) and continental polar (cP) air masses. **B.** Block diagram of a warm-type occluded front.



A.



B.

Drylines

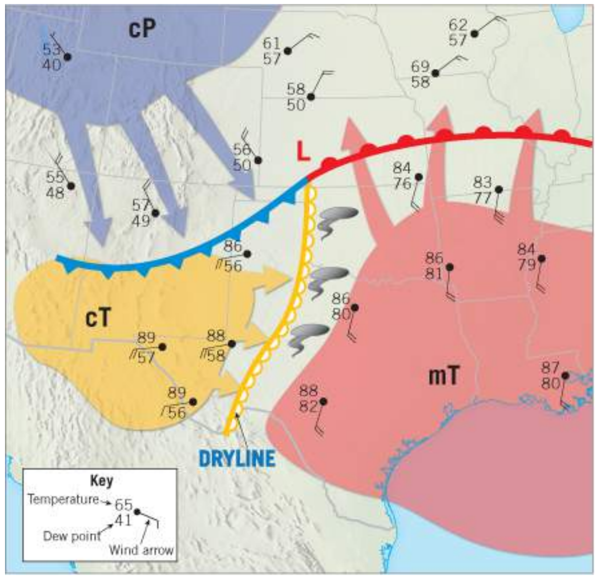
Although most fronts separate air masses of different temperatures, frontal boundaries can also separate air masses having different humidity. All other factors being equal, dry air is denser than humid air. Therefore, when a dry, warm air mass advances into a region occupied by an equally warm but more humid air mass, a type of frontal boundary called a **dryline** develops.

> Drylines form when warm, dry air encounters warm, moist air.

Drylines most often develop over the southern Great Plains when dry, continental tropical (cT) air originating in the Southwest meets moist, maritime tropical (mT) air from the Gulf of Mexico. Drylines are spring and summer phenomena, most often generating a band of severe thunderstorms along a line extending from Texas to Nebraska that moves eastward across the Great Plains. A dryline is easily identified by comparing the dew-point temperatures of the cT air west of the boundary with the dew points of the mT air mass to the east (Figure 9.7).

Figure 9.7 Dryline

This dryline developed over Texas and Oklahoma and generated thunderstorms and tornadoes. Notice that the dry (low–dew point) cT air is pushing eastward and displacing warm, moist mT air. The result is weather that resembles a rapidly moving cold front.



Concept Checks 9.1

- Compare the weather of a typical warm front with that of a typical cold front.
- How does a stationary front produce precipitation when its position does not change or changes very slowly?
- In what way are drylines different from warm and cold fronts?

9.2 Midlatitude Cyclones and the Polar-Front Theory

LO 2 Outline the stages in the life cycle of a typical midlatitude cyclone.

Midlatitude cyclones, or **middle-latitude cyclones**, are synoptic-scale, low-pressure systems with diameters that often exceed 1000 kilometers (600 miles) and travel from west to east across the middle latitudes in both hemispheres (see Figure 9.1). Lasting from a few days to more than a week, a midlatitude cyclone in the Northern Hemisphere has a counterclockwise circulation pattern, with airflow directed inward toward its center. In the early stage of development, midlatitude cyclones have a cold front as well as a warm front extending from the central area of low pressure. Oriented roughly west-to-east, the cold front lies left (west) of the center of low pressure, whereas the warm front is located to the right (east). Surface convergence and ascending air along the fronts initiate cloud development that frequently produces precipitation.

Polar-Front Theory

As early as the 1800s, cyclones were known to be bearers of precipitation and severe weather. Thus, the barometer was established as the primary tool in forecasting day-to-day weather changes. However, this early method of weather prediction largely ignored the role of air-mass interactions in the formation of these weather systems. Consequently, it was impossible to pinpoint the conditions favorable to cyclone development.

The first comprehensive model of cyclone development and intensification was formulated by a group of Norwegian scientists during World War I. German restrictions on international communications to Norway—including critical weather reports pertaining to conditions in the Atlantic Ocean—led to the establishment of a closely spaced network of weather stations throughout Norway. Using this network, Norwegian-trained meteorologists greatly advanced the understanding of weather associated with midlatitude cyclones.

In 1921, the work of these scientists resulted in a publication outlining a compelling model of how midlatitude cyclones progress through stages of birth, growth, and decay. These insights, which marked a turning point in atmospheric science, became known as the **polar-front theory**—also referred to as the **Norwegian cyclone model**. Even without the benefit of upper-air charts, these skilled meteorologists presented a model that remains remarkably applicable in modern meteorology.

> The polar-front theory was the first model to explain the development and evolution of a midlatitude cyclone.

In the Norwegian cyclone model, midlatitude cyclones develop in conjunction with polar fronts. Recall that polar fronts separate cold polar air from warm subtropical air (see Chapter 7). During the cold season, polar fronts are generally well defined and form a nearly continuous west-to-east running band around Earth recognizable on upper-air charts. At the surface, this frontal zone is often broken into distinct segments separated by regions of gradual temperature changes. It is along these frontal zones that cold, equatorward-moving air collides with warm, poleward-moving air to produce most midlatitude cyclones.

You might have wondered . . .

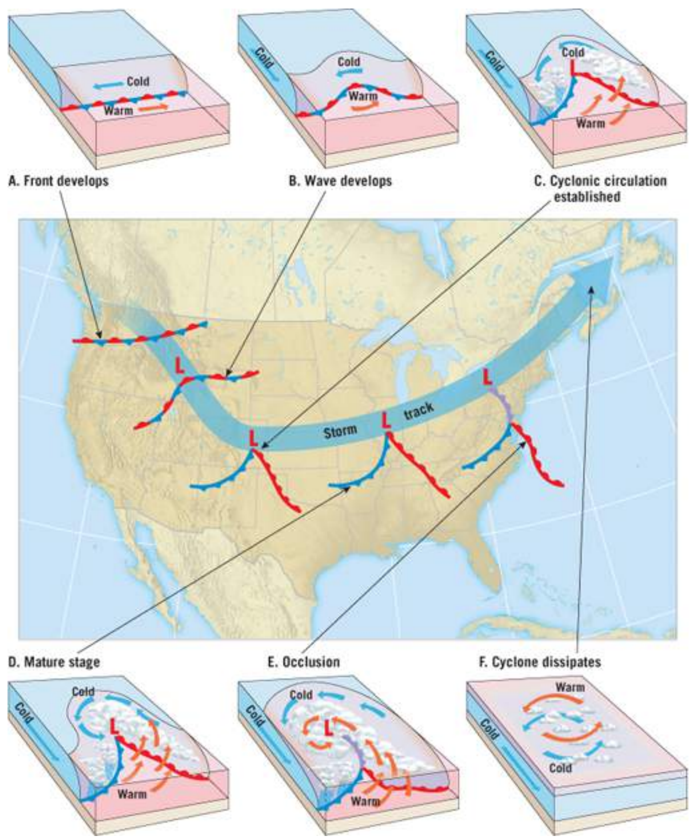
What is an extratropical cyclone?

Meaning "outside the tropics," *extratropical* is simply another name for a midlatitude cyclone. The term *cyclone* refers to the circulation around any low-pressure center, regardless of its size or intensity. Hence, midlatitude cyclones and hurricanes are two types of cyclones; *extratropical cyclone* is another name for a midlatitude cyclone, and *tropical cyclone* is often used to describe a hurricane.

Life Cycle of a Midlatitude Cyclone

According to the Norwegian model, cyclones form along fronts and proceed through a generally predictable life cycle. The development and strengthening of these storm systems is called **cyclogenesis**—a process that can last from a few days to more than a week, depending on atmospheric conditions. The stages in the life of a typical midlatitude cyclone are illustrated in Figure 9.8.

Figure 9.8 Stages in the life cycle of a midlatitude cyclone



The polar-front theory describes six stages in the lifecycle of a cyclone, starting with a clash of two air masses along the polar front and ending with dissipation of the low.

Formation: Two Air Masses Clash

A midlatitude cyclone is born when two air masses of different densities (temperatures) move roughly parallel to a front but in opposite directions (Figure 9.8A). In the classic polar-front model, this would be continental polar (cP) air associated with the *polar easterlies* on the north side of the front and maritime tropical (mT) air driven by the *westerlies* on the south side of the front.

A Wave Develops

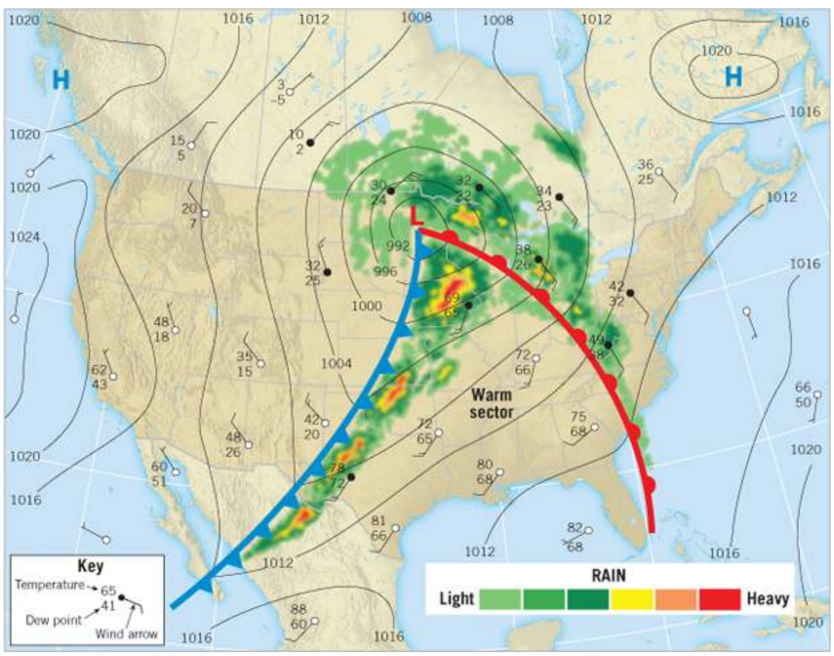
Under conditions that will be described later, the frontal surface that separates these two contrasting air masses takes the shape of a wave that is usually several hundred kilometers long (Figure 9.8B). These waves are like, but much larger than, swells that form on water. Some waves tend to dampen or die out, whereas others grow in amplitude. As these storms intensify, or "deepen," the waves change shape, much as a gentle ocean swell does as it moves into shallow water and becomes a tall, breaking wave.

Cyclonic Flow

As a wave evolves, warm air advances poleward to form a warm front, while cold air moves equatorward to form a cold front (Figure 9.8C). This change in the direction of the surface flow is accompanied by a readjustment in the pressure pattern and results in somewhat circular isobars, with the lowest pressure located at the crest of the wave. The resulting flow is counterclockwise toward the center of the low, which can be seen clearly on the weather map shown in Figure 9.9.

Figure 9.9 Simplified surface weather map showing the circulation of a midlatitude cyclone

The color of an area indicates the intensity of precipitation.



Watch **Animation: Midlatitude Cyclones**

Once the cyclonic circulation develops, convergence results in forceful lifting, especially where warm air is overrunning colder air. Figure 9.9 illustrates that the air in the *warm sector* (behind the warm front; on this map, over the southern states) is flowing northeastward, toward cooler air that is flowing toward the northwest. Because the warm air is moving perpendicular to the front, we can conclude that the warm air is invading a region formerly occupied by cooler air. Therefore, this must be a warm front. Similar reasoning indicates that to the left (west) of the wave front, cold air from the northwest is displacing the air of the warm sector and generating a cold front.

Eye on the Atmosphere 9.2

This image of a line of clouds was taken by astronauts aboard the International Space Station. The dashed line on the image shows the approximate surface position of the front responsible for the cloud development. Assume that this front is located over the central United States as you answer the following questions.

Apply What You Know

1. What is the cloud type of the tallest clouds in this image?
2. Is the cloud pattern shown typical of a cold front or a warm front?
3. Is this front moving toward the southeast or toward the northwest?
4. Is the air mass located to the southeast of the front a continental polar (cP) or a maritime tropical (mT) air mass?

Cyclonic storms develop further when there is a region of divergence aloft, directly above the developing low-pressure system at the surface. The divergence aloft helps lift the air converging at the surface, thereby compensating for the surface inflow. Thus, the cyclone continues to strengthen by bringing mT air into the warm sector and by pulling cP air into the cold sector.

> Upper-level support causes a cyclonic storm to develop further, where diverging airflow aloft creates lower pressure at the surface.

Mature Stage

During the *mature stage* of a midlatitude cyclone, both the warm and cold fronts strengthen as the storm migrates toward the northeast (Figure 9.8D). The mature stage is generally characterized by a strong cold front, which may produce severe thunderstorms, damaging winds, and even tornadoes. The warm front has a well-established cloud layer ahead of it that tends to produce a broad band of precipitation. At the end of the mature stage, the low continues to deepen as the cold front gradually overtakes the warm front to produce an occluded front.

Occlusion: Beginning of the End

Recall that occlusion begins as a cold front starts to overtake (lift) the warm front (Figure 9.8E). The early occluded stage often produces the most hazardous weather, but it can be quite varied, depending on the season and one's location in relation to the cyclonic storm. In winter, a place directly north of an occluded front might experience blizzard conditions and heavy snowfall, whereas the weather ahead of the warm front may consist of freezing rain. The southward extending cold front will often produce severe thunderstorms. In midsummer, midlatitude cyclones tend to be weaker and affect mainly the northern tier of the United States and Canada.

The Storm Dissipates

As the cold front continues to overtake the warm front, the occluded front lengthens, and the warm sector is increasingly displaced aloft. This, in turn, displaces the surface low so it is no longer directly beneath the zone of upper-level divergence. Without the support of airflow aloft, air rushing into the center of the low causes the surface pressure gradient to weaken, as does the storm itself. The concept of upper-level support is explored further in the next section.

Within a day or two the entire warm sector is forced aloft, and cold air surrounds the cyclone at Earth's surface (Figure 9.8F). This largely eliminates the horizontal temperature (density) difference that existed between the two contrasting air masses, at which point the cyclone has exhausted its source of energy. Friction slows the surface flow, and the once highly organized, inward-directed counterclockwise flow ceases to exist.

A simple analogy may help you visualize what happens to the cold and warm air masses in the preceding discussion. Imagine a large water tank with a vertical divider separating it into two equal parts. Half of the tank is filled with hot water dyed red, and the other half is filled with blue-dyed, icy cold water. Now imagine what happens when the divider is removed. The cold, dense water will flow under the less-dense warm water, displacing it upward. This rush of water will stop when the red colored warm water is displaced over the top of blue colored cold water. Similarly, a midlatitude cyclone dies when all the warm air surrounding the low is displaced aloft and the horizontal discontinuity between the air masses no longer exists.

> A midlatitude cyclone dies when all the warm air surrounding the surface low is displaced aloft and the horizontal discontinuity between the warm and cold air masses no longer exists.

Concept Checks 9.2

- Briefly describe four characteristics of a midlatitude cyclone.
- Explain the life cycle of a midlatitude cyclone according to the polar-front theory.
- Describe how a midlatitude cyclone creates warm and cold fronts.

9.3 Flow Aloft and Cyclone Formation

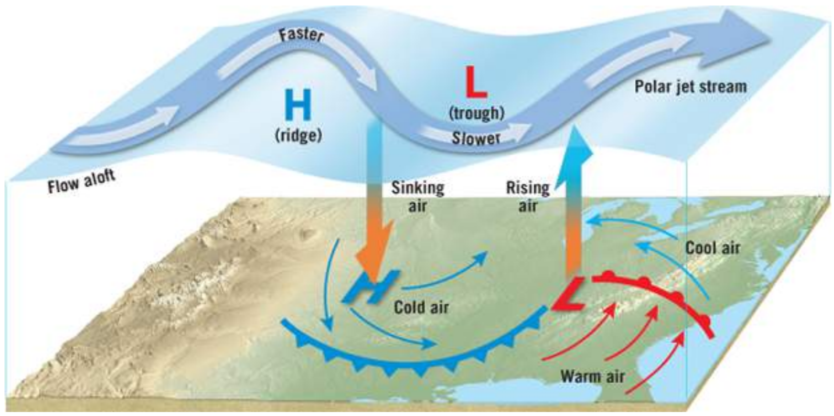
LO 3 Relate divergence in airflow aloft to the development and intensification of a midlatitude cyclone at the surface.

Recall that in the polar-front model, cyclogenesis occurs where a frontal surface is distorted and becomes shaped like an ocean wave. Several factors are thought to produce this wave in a frontal zone. Topographic irregularities (such as mountains), temperature contrasts (as between sea and land), or ocean current influences can disrupt the relatively straight, west-to-east *zonal* flow sufficiently to produce a wave along a front. In addition to these surface factors, a strong jet stream in the flow aloft frequently precedes the formation of a surface cyclone. In fact, meanders in the upper-level flow contribute to the formation as well as the strengthening of these rotating storm systems.

When winds aloft exhibit zonal flow, little cyclonic activity occurs at the surface. However, cyclonic activity intensifies when the jet stream begins to meander widely from north to south in a *meridional flow* pattern, forming high-amplitude rising waves of alternating troughs (lows) and ridges (highs). Notice in Figure 9.10 that when surface cyclones form, they are usually centered below the jet stream and downwind (east) of an upper-level low (trough).

Figure 9.10 Relationship between the meandering flow in the jet stream aloft and cyclone development at the surface

Midlatitude cyclones tend to form downstream of an upper-level low (trough).



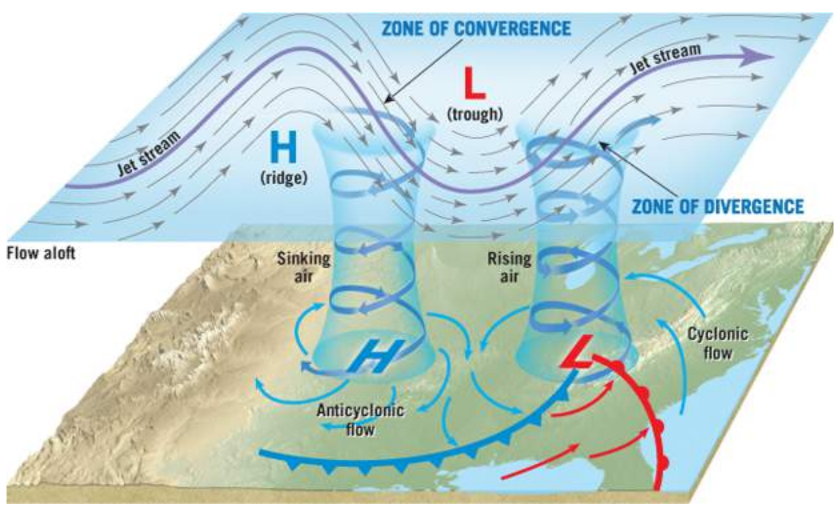
Watch Video: A Midlatitude Cyclone's Effects on Society

Cyclonic and Anticyclonic Circulation

Before discussing how surface cyclones are generated and supported by the flow aloft, let us review the nature of cyclonic and anticyclonic winds. Recall that in the Northern Hemisphere, airflow around a surface low is counterclockwise and inward, which leads to mass convergence (coming together) at the surface. Because the accumulation of air is accompanied by a corresponding increase in surface pressure, we would expect a surface low-pressure center to "fill" rapidly and be eliminated, just as the vacuum in a coffee can is quickly equalized when opened. When this occurs in a cyclonic storm, the surface pressure rises and the storm weakens, a process called *filling*.

However, cyclones often exist for a week or longer. For this to occur, surface convergence must be offset by rising air in the column and divergence aloft (Figure 9.11). As long as outflow aloft is greater (more air is removed) than the amount of air that arrives at the surface (convergence), the low pressure at the surface will intensify. This process is termed *deepening*.

Figure 9.11 Idealized view of divergence and convergence aloft that supports cyclonic and anticyclonic circulation at the surface



Surface anticyclones, where the airflow is clockwise and outward, are also supported by the flow aloft. In an anticyclone, divergence at the surface must be exceeded by convergence aloft and general subsidence (sinking) of the air column for the system to intensify (Figure 9.11).

> A surface low pressure is characterized by convergence, while high pressure at the surface exhibits divergence.

Because cyclones bring stormy weather, they have received far more attention than their counterparts, anticyclones. Yet the close relationship between them makes it difficult to separate a discussion of these two pressure systems. The surface air that feeds a cyclone generally originates as surface air flowing out of an anticyclone (Figure 9.11). Consequently, cyclones and anticyclones are typically found adjacent to one another.

Divergence and Convergence Aloft

Recall that unlike divergence at Earth's surface, divergence in the airflow aloft does not produce outward flow in all directions. Instead, the winds aloft generally flow from west to east along sweeping curves. How does zonal flow aloft cause upper-level divergence?

One mechanism responsible for divergence aloft is a phenomenon known as *speed divergence*. On entering a zone of high wind speed, air accelerates and stretches out (divergence). In contrast, when air enters a zone of slower wind speed, an air pileup (convergence) results. Analogous situations occur every day on a toll highway. As automobiles slow to pay the toll, they experience convergence (coming together). When exiting a toll area and entering the zone of maximum speed, we find automobiles diverging (increasing the number of car lengths between them).

Recall from Chapter 6 that winds are typically *slower* (subgeostrophic) around a low (or trough) and *faster* (supergeostrophic) around an upper-level high (or ridge). (*Hint:* Remember that winds are s*low* around a *low*.) As a result, winds flowing from a ridge to a trough slow down and result in convergence, whereas winds moving from a trough to a ridge speed up and produce divergence.

> Winds flowing from a ridge toward a trough slow down (converge), whereas winds moving away from a trough toward a ridge speed up (diverge).

In addition to speed divergence, other factors contribute to divergence (or convergence) aloft. These include *directional divergence* and *directional convergence*, which result from changes in wind direction. For example, directional convergence is the result of air being funneled into a restricted area. On an upper-air chart, convergence occurs in regions where height contours move progressively closer together. Returning to our interstate highway analogy, convergence occurs where a crowded three-lane highway is reduced to two lanes because of road construction. Directional divergence, the opposite phenomenon, is analogous to the location where the two lanes change back to three.

The combined effect of these and other factors leads to an area of upper-air divergence and corresponding surface cyclonic circulation that generally develops downstream from an upper-level, low pressure trough, as illustrated in Figure 9.11. As long as divergence aloft exceeds convergence at ground level, surface pressures will fall, and the cyclonic storm will intensify.

Conversely, the zone in the jet stream that experiences upper-air convergence, and corresponding surface anticyclonic rotation, is located downstream from a ridge, or an upper-level high (Figure 9.11). The accumulation of air in this region of the jet stream leads to subsidence (sinking) and increased surface pressure. Hence, it is a favorable site for the development of a surface anticyclone.

> Divergence aloft enhances a surface low, while convergence aloft enhances a surface high.

Flow Aloft and Cyclone Migration

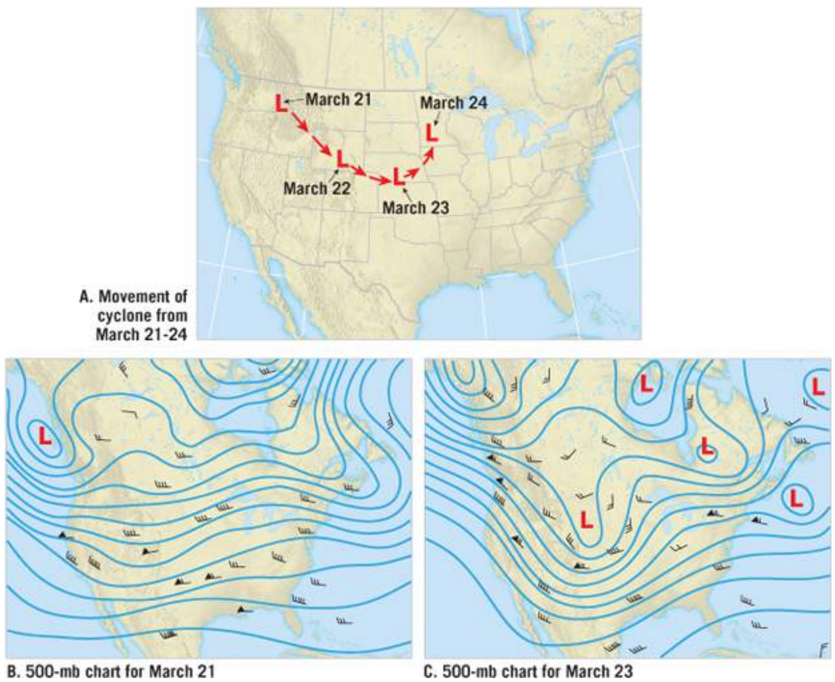
The wavy airflow aloft not only influences the development and intensity of a surface cyclonic storm, but also affects cyclone movement. Middle- and upper-troposphere flow strongly influences the rate at which these pressure systems advance and the direction they follow. Generally, surface cyclones move in the same direction as winds aloft at the 500-millibar level, but at about one-quarter to one-half the speed. Normally these systems travel at 25 to 50 kilometers (15 to 30 miles) per hour, advancing roughly 600 to 1200 kilometers (400 to 800 miles) daily. Cyclones travel the fastest during the coldest months, when temperature gradients in the middle latitudes are steepest.

> The movement of midlatitude cyclones is controlled by steering winds in the middle troposphere.

Let us examine an example of this steering effect by seeing how changes in the upper-level flow correspond to changes in the path taken by a cyclone. Figure 9.12A illustrates the changing position of a midlatitude cyclone over a 4-day period. Notice in Figure 9.12B that on March 21, the 500-millibar contours are relatively straight. Also notice that for the following 2 days, the cyclone moves in a southeasterly direction. By March 23, the 500-millibar contours make a sharp bend northward on the eastern side of a trough situated over Wyoming (Figure 9.12C). Likewise, the path of the cyclone makes a similar northward migration the next day.

Figure 9.12 **Steering of midlatitude cyclones by the flow aloft**

A. Notice that the cyclone (low) moved almost in a straight southeastward direction on March 21 and March 22. On the morning of March 23, the path of the storm abruptly turned northward. **B.** This upper-air chart shows that the contours were relatively straight on March 21. **C.** Notice that the change in direction of the cyclone′s path corresponded to a similar change in upper-level flow shown on the chart for March 23.



Retrospectively, this example illustrates the influence of upper airflow on cyclonic movement. Therefore, useful predictions of cyclone movements require accurate appraisals of changes in the westerly flow aloft *beforehand*. Measuring and predicting the behavior of the wavy flow in the middle and upper troposphere is an important part of modern weather forecasting. In fact, meteorologists launch weather balloons twice daily at numerous global locations to gather data on the airflow aloft to make more accurate predictions.

Concept Checks 9.3

- Briefly explain how the flow aloft maintains and strengthens cyclones at the surface.
- Given an upper-air chart, where do forecasters usually look to find favorable sites for cyclogenesis? Where do anticyclones usually form in relation to the wavy flow aloft?
- Describe the motion of a midlatitude cyclone in relation to the flow at the 500-millibar level.

9.4 A Modern View: The Conveyor Belt Model

LO 4 Explain the conveyor belt model of a midlatitude cyclone and describe the three interacting air streams on which it is based.

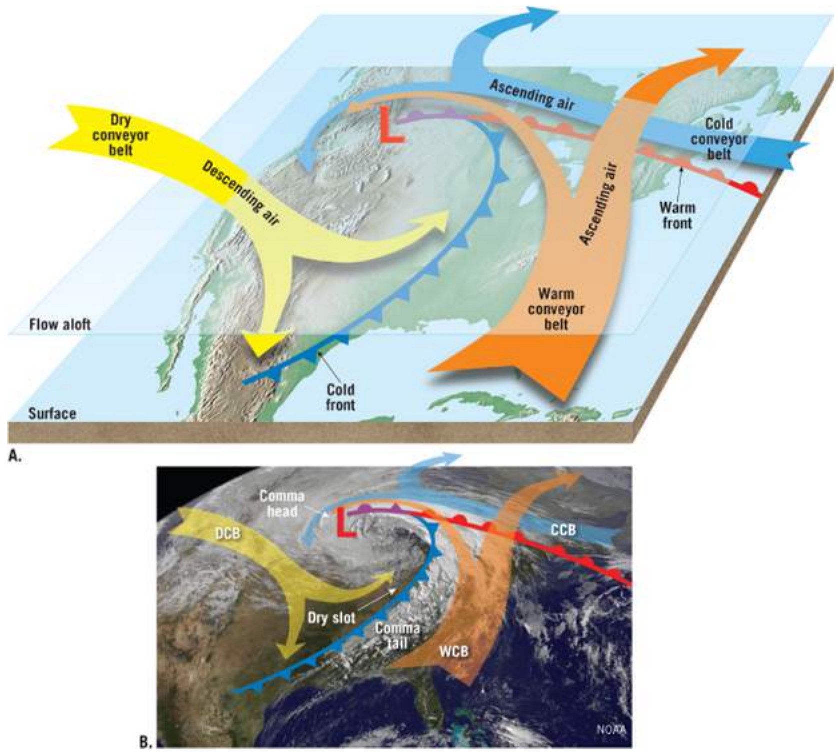
The polar-front model, or Norwegian cyclone model, has proven to be a valuable tool for describing the formation and development of midlatitude cyclones over time. Although more current research has not replaced this model, upper-air and satellite data provide meteorologists with a more thorough understanding of the three-dimensional flow around a midlatitude cyclone.

The new way of describing the flow within a cyclone calls for a new analogy. Recall that the Norwegian model describes cyclone development in terms of the interactions of air masses along frontal boundaries, similar to armies clashing along battlefronts. The new model employs a modern example from industry—conveyor belts. Just as conveyor belts transport goods or people from one location to another, atmospheric conveyor belts transport air with distinct characteristics from one location to another.

This modern view of cyclogenesis, called the **conveyor belt model**, provides a good picture of the airflow within a cyclonic system. It also helps explain the shape of a typical midlatitude cyclone. The conveyer belt model consists of three interacting air streams: two that originate near Earth's surface and ascend, and a third that originates in the uppermost troposphere and descends. A schematic representation of these air streams is shown in Figure 9.13A.

Figure 9.13 Schematic drawing of the circulation of a mature midlatitude cyclone, showing the conveyor belts

A. The warm conveyer belt is shown in orange, the cold conveyor belt in blue, and the dry conveyor belt in yellow. **B.** The corresponding cloud cover produced by the warm and cold conveyor belts and the dry slot produced by the dry conveyor belt are shown here.



The conveyor belt model describes 3-dimensional flow in a midlatitude cyclone.

Warm Conveyor Belt

The **warm conveyor belt** (shown in orange) is the main source of warm, moist air feeding the cyclone. In North America, the Gulf of Mexico is the major source of the warm, humid air that flows into the warm sector of the developing midlatitude cyclone (Figure 9.13A). This air stream flows northward, roughly parallel to the cold front. As the warm conveyor belt approaches the warm front, it slowly begins to rise. When it reaches the sloping boundary of the warm front, it rises even more rapidly over the cool air that lies beyond (poleward of) the front. When a well-organized midlatitude cyclone has a good supply of moisture, abundant precipitation results.

> The warm conveyor belt is the main moisture source in a midlatitude cyclone.

During its ascent, this warm, humid air cools adiabatically and produces a wide band of clouds and precipitation. Depending on atmospheric conditions, rain, drizzle, freezing rain, and snow are possible. When this air stream reaches the middle troposphere, it begins to turn right (eastward) and eventually joins the general west-to-east flow aloft. In the later stages of the life cycle of a midlatitude, a portion of the warm conveyor belt is deflected westward, wrapping around the center of low pressure (Figure 9.13A).

> The warm conveyor belt originates near the surface in the warm sector and ascends over cooler air north of the warm front.

Cold Conveyor Belt

The **cold conveyor belt** (blue arrow) is airflow that starts at the surface ahead (poleward) of the warm front and flows westward toward the center of the cyclone (Figure 9.13A). Flowing beneath the warm conveyor belt, this air is moistened by the evaporation of raindrops falling through it. Near the Atlantic Ocean, this conveyor belt has a marine origin and feeds significant moisture into the storm. Convergence causes this air stream to rise as it nears the cyclone's center. During its ascent, this air cools adiabatically, becomes saturated, and contributes to the cyclone's precipitation.

> The cold conveyor belt originates near the ground ahead of the warm front and ascends as it wraps around the low.

As the cold conveyor belt reaches the middle troposphere, some of the flow rotates cyclonically around the low to produce the distinctive "comma head" of the mature storm system (Figure 9.13B). The remaining flow turns right (clockwise) and becomes incorporated into the general westerly flow. Here it parallels the flow of the warm conveyor belt and may generate precipitation.

You might have wondered . . .

Why are winter storms now being named?

Beginning in the 2012–2013 winter season, The Weather Channel began naming noteworthy winter storms. Europe has been naming storms for some time, and the United States has been naming hurricanes and tropical storms since the 1940s. In the United States, a few major winter storms have been given informal names, including the “President’s Day Storm” of 2003. The lack of a formal naming system may stem from the fact that we have no national center for winter storms, like the National Hurricane Center, which monitors tropical cyclones.

Dry Conveyor Belt

The third air stream, called the **dry conveyor belt**, is shown as a yellow arrow in Figure 9.13A. Whereas both the warm and cold conveyor belts begin at the surface, the dry air stream originates in the uppermost troposphere, where moisture is scarce. As part of the upper-level westerly flow, the dry conveyor belt is quite cold and dry.

As this air stream enters the cyclone, it splits. One branch descends behind the cold front, resulting in the clear, cool conditions normally associated with the passage of a cold front. In addition, this flow maintains the strong temperature contrast observed across the cold front. The other branch of the dry conveyor belt wraps cyclonically (counterclockwise) around the low and forms the *dry slot* (cloudless area) that separates the head and tail of the comma cloud pattern (Figure 9.13B).

> The dry conveyor belt originates in the upper troposphere and descends toward the cold front, resulting in clear, cool conditions.

Concept Checks 9.4

- Briefly describe the conveyor belt model of midlatitude cyclones.
- What is the source of air carried by the warm conveyor belt?
- In what way is the dry conveyor belt different from both the warm and cold conveyor belts?

9.5 Where Do Midlatitude Cyclones Form?

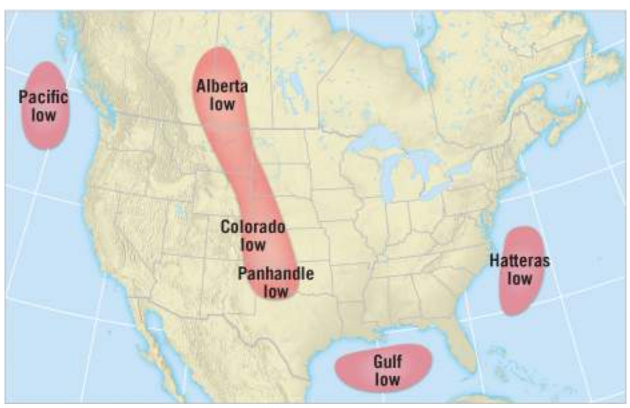
LO 5 Identify on a map the primary sites for the development of midlatitude cyclones affecting North America. Indicate typical paths for Alberta clippers, Colorado lows, Panhandle lows, Gulf lows, and nor′easters.

The development of midlatitude cyclones does not occur uniformly over Earth′s surface but tends to favor certain locations, such as the leeward (eastern) sides of mountains and along coastal areas. In general, midlatitude cyclones form in areas where significant temperature contrasts occur in the lower troposphere.

Sites of Midlatitude Cyclone Formation That Affect North America

Figure 9.14 shows the main areas of cyclone development over North America and adjacent oceans. Notice that a prime site for cyclone formation is along the east side of the Rocky Mountains. As the westerly flow meets the Rockies, the mountainous terrains slows the low-level flow, while the air aloft continues uninhibited on its eastward path. When the upper-level flow reaches the eastern slopes of the Rockies, it produces a trough in the flow aloft, which enhances the development of a surface low. Three common cyclones that form east of the Rockies are called the Colorado low, Panhandle low, and the Alberta low. Once formed, these cyclones are fed at lower levels by warm, moist Gulf air, whereas the air flowing into these lows from the north is relatively cold.

Figure 9.14 Sites of cyclone formation



These temperature differences can produce intense low-pressure systems that migrate northeastward across the United States. In winter and spring, sleet and freezing rain can form along the warm front, strong thunderstorms are associated with the cold front, and heavy snowfall usually occurs north of the storm's center. These cyclones, therefore, provide most of the winter moisture to the central part of the United States.

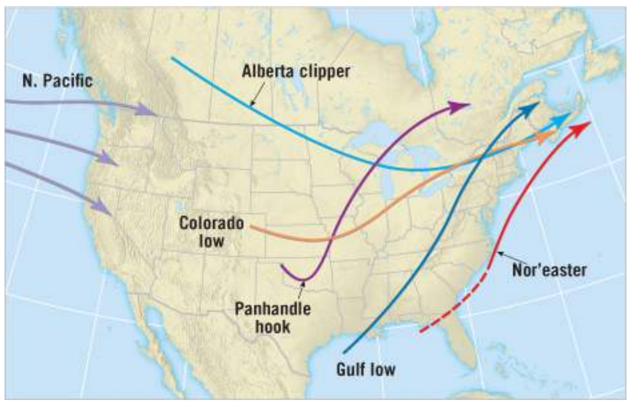
> Midlatitude cyclones tend to form downwind of mountains and along coastlines.

Other important sites of cyclone development are in the North Pacific, along the North Atlantic coastal areas, and in the Gulf of Mexico. These are areas of temperature contrasts between relatively warm ocean waters and a cool landmass. For example, midlatitude cyclones that develop over the Hatteras low form along the boundary between the warm waters of the Gulf Stream and cold Atlantic coast (Figure 9.14). These storms, with a vast source of moisture from the warm ocean waters, can develop quickly, creating pressure drops of over 24 millibars in a single day. As a result, these systems are capable of producing flooding or heavy snowfall along the eastern seaboard. When they move northeastward, these storms are called *nor'easters*.

Patterns of Movement

Once formed, most midlatitude cyclones tend to travel in an easterly direction across North America and then follow a more northeasterly path into the North Atlantic (Figure 9.15). However, numerous exceptions occur.

Figure 9.15 Typical paths of cyclonic storms that affect the lower 48 states



Movement of North Pacific Lows

Midlatitude cyclones that influence western North America originate mainly over the North Pacific. Many of these systems migrate from the Gulf of Alaska and affect Alaska and western Canada. However, during the winter months, these storms travel farther southward and often reach the west coast of the contiguous 48 states, sometimes traveling as far south as southern California. These low-pressure systems provide the winter rainy season that affects much of the west coast.

> Midlatitude cyclones move eastward or northeastward.

Most Pacific storms diminish in strength as they cross the Rockies, but they often redevelop on the eastern side of these mountains. A common area for redevelopment is Colorado, but other sites exist as far south as Texas and as far north as Alberta, Canada. Cyclones that redevelop over the Great Plains generally migrate eastward until they reach the central United States, where they follow a northeastward or even northward trajectory. Many of these cyclones traverse the Great Lakes region, making it one of the most storm-ridden portions of the country. In addition, some storms develop off the coast of the Carolinas and tend to move northward with the warm Gulf Stream, bringing stormy conditions to the entire Northeast.

Movement of Panhandle and Colorado Lows

Panhandle and Colorado low pressure systems are similar, differing mainly in their region of origin. Panhandle lows, which form near the Texas and Oklahoma panhandles, first travel toward the southeast and then bend and travel sharply northward across Wisconsin and into Canada. As a result, they are known as the *Panhandle hook*—the “hook” describes the curved path these storms follow (Figure 9.15).

Colorado lows form a bit farther north but also dip southward and then take a more northeasterly path. Although they can form in any season, Colorado lows are most common in the fall, winter, and spring. In the spring, the early stage of a Colorado low is also likely to have a dryline associated with it, which can enhance the stormy conditions associated with these systems.

Alberta Clipper

An *Alberta clipper* is a cold, windy cyclonic storm that forms on the eastern side of the Canadian Rockies in the province of Alberta (Figure 9.15). Noted for their speed, they are called "clippers" because in colonial times, the fastest vehicles were small ships by the same name. Alberta clippers dive southeastward into Montana or the Dakotas and then track across the Great Lakes, bringing dramatically lower temperatures. Winds associated with clippers frequently exceed 50 kilometers (30 miles) per hour.

Because clippers move rapidly and remain great distances from the mild waters of the Gulf of Mexico, they tend to be moisture deprived and do not drop large amounts of snow. Instead, they may leave a few inches in a narrow band from the Dakotas to New York over a span as short as 2 days. However, because these winter storms are relatively frequent occurrences, they make a significant contribution to the total winter snowfall in the northern tier of states. These cyclones are most common in the coldest part of winter.

Nor'easter

The classic storm that travels from the Mid-Atlantic coast to New England is called a *nor'easter* because the winds preceding these storms are from the northeast (Figure 9.15). Nor'easters are most frequent and violent between September and April, when cold air pouring south from Canada meets relatively warm, humid air from the Atlantic. Once formed, a nor'easter follows the coast and often brings rain, sleet, and heavy snowfall to the Northeast. The circulation produces strong on-shore winds, making these storms responsible for considerable coastal erosion, flooding, and property damage. A classic nor'easter is described in Chapter 8, page 211.

Gulf Lows

As the name implies, Gulf lows form over the Gulf of Mexico. These storms move northeastward, carrying warm moist air into the eastern United States. Some travel west of the Appalachians, where they can bring heavy snowfall in the winter. Others flow east of the Appalachians and draw in moist air from the Atlantic, often becoming intense nor’easter storm systems.

Concept Checks 9.5

- List four locations where midlatitude cyclones that affect North America tend to form.
- Which cyclones mostly affect the central part of the United States?
- Which cyclones mainly affect the east coast? The west coast?

9.6 Idealized Weather of a Midlatitude Cyclone

LO 6 Describe the general weather conditions associated with the passage of a mature midlatitude cyclone.

Guided by the westerlies aloft, cyclones generally move eastward across the United States. Therefore, we can expect the first signs of a cyclone's arrival to appear in the western sky. Upon reaching the Mississippi Valley, however, cyclones often begin a more northeasterly trajectory and occasionally move directly northward. Typically, a midlatitude cyclone requires 2 or more days to pass completely over a region. During that span, abrupt changes in atmospheric conditions may occur, particularly in late winter and spring, when the greatest temperature contrasts occur across the middle latitudes.

Figure 9.16 illustrates a mature midlatitude cyclone; note the distribution of clouds and thus the regions of possible precipitation. Compare this map to the satellite image of a cyclone in Figure 9.17. It is easy to see why we often describe the cloud pattern of a cyclone as having a "comma" shape.

Figure 9.16 **Cloud and precipitation patterns typically associated with a mature midlatitude cyclone**

Above the map is a vertical cross section along line *F*–*G*. The middle section is a map view with lines showing the surface positions of the cross sections. Below the map is a cross section along *A*–*E*. For cloud abbreviations, refer to Figures 9.2 and 9.3.

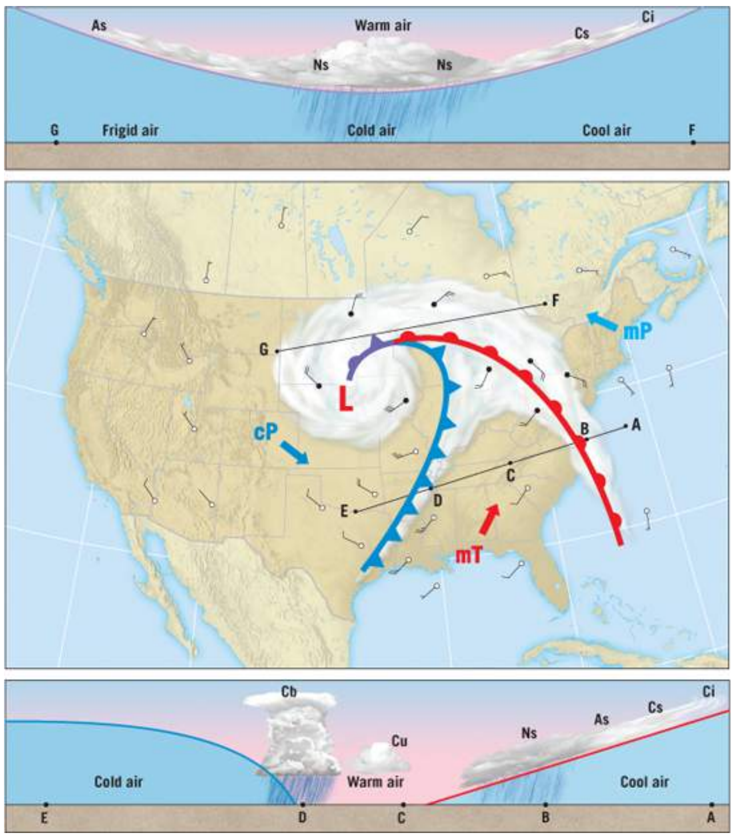
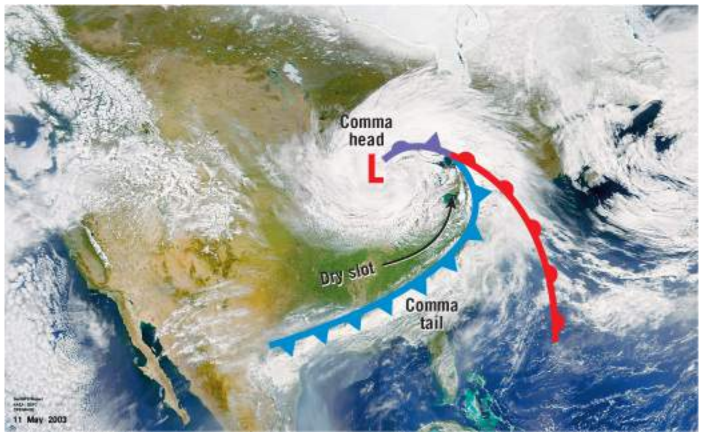


Figure 9.17 Satellite view of a mature midlatitude cyclone over the eastern half of the United States

It is easy to see why we often refer to the cloud pattern of a cyclone as having a “comma” shape.



Depending on your location, two vastly different types of weather can be expected. First, imagine the change in weather as you move from right to left along profile *A*–*E* (see Figure 9.16). At point *A*, the sighting of cirrus clouds is the first sign of the approaching cyclone. These high clouds can precede the surface front by 1000 kilometers (600 miles) or more and are normally accompanied by falling pressure. As the warm front advances, lowering and thickening of the cloud deck occurs. Within 12 to 24 hours after the first sighting of cirrus clouds, light precipitation usually commences (point *B*). As the front nears, the rate of precipitation increases, the temperature rises, and winds begin to change from an easterly to a southwesterly flow. During the warm season, precipitation comes in the form of rain, which can be heavy at times. By contrast, during cooler weather, sleet and freezing rain can occur.

> The weather you experience during a midlatitude cyclone depends on where you are relative to the location of the low.

With the passage of the warm front, the warm sector west of the front is under the influence of a maritime tropical (mT) air mass (point *C*). Depending on the season, the region affected by this part of the cyclone experiences warm to hot temperatures, southwesterly winds, high humidity, and clear to partly cloudy skies containing cumulus or cumulonimbus clouds.

The warm conditions associated with the warm sector are quickly replaced by gusty winds and precipitation generated along the cold front. The approach of a rapidly advancing cold front is marked by a wall of rolling black clouds (point *D*). Severe weather accompanied by heavy precipitation, and occasionally hail or tornadoes, can be expected.

The passage of the cold front is easily detected by a dramatic shift in wind direction. The warm flow from the south or southwest is replaced by cold winds from the west to northwest, resulting in a pronounced decrease in temperature. Also, rising pressure hints of the subsiding cool, dry air behind the cold front. Once the front passes, the skies clear quickly as cooler, drier air invades the region (point *E*). This often results in a day or two of almost cloudless blue skies.

A very different set of weather conditions prevails in the portion of the cyclone located north of the center of low pressure—profile *F*–*G* at the top of Figure 9.16. In this part of the storm, temperatures remain cool. The first hints of the approaching low-pressure center are a continual drop in air pressure and increasingly overcast conditions that bring varying amounts of precipitation. This section of the cyclone most often generates heavy snowfall during the winter months and heavy rain in the spring.

Once the process of occlusion begins, the character of the storm changes. Because occluded fronts tend to move more slowly than other fronts, the entire wishbone-shaped frontal structure shown in Figure 9.16 rotates counterclockwise. As a result, the occluded front appears to “bend over backward” and thus influences the region as it lingers for a few days.

Keeping in mind what you’ve learned so far may help you understand, and possibly anticipate, changes in daily weather.

Concept Checks 9.6

- Briefly describe the weather associated with the passage of a mature midlatitude cyclone when the center of low pressure is located about 200 to 300 kilometers north of your location.
- If the midlatitude cyclone described in Question 1 took 3 days to pass your location, on which day would the temperatures be the warmest? On which day would the temperatures be the coldest?
- What winter weather is expected with the passage of a mature midlatitude cyclone when the center of low pressure passes about 100 to 200 kilometers south of your location?

9.7 Anticyclonic Weather and Atmospheric Blocking

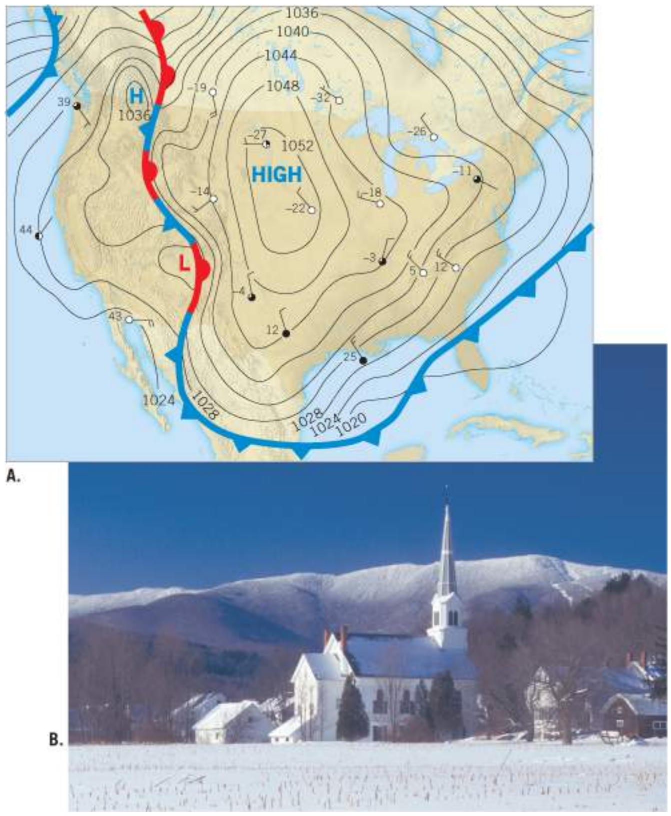
LO 7 Define a blocking high-pressure system and explain how it influences weather over the midlatitudes.

The gradual subsidence within anticyclones generally produces clear skies and calm conditions. Because these high-pressure systems are not associated with stormy weather, both their development and movement have not been studied as extensively as those of midlatitude cyclones.

However, anticyclones do not always bring desirable weather. Large anticyclones often develop over the Arctic during the winter. These cold high-pressure centers are known to migrate as far south as the Gulf coast, where they can impact weather over more than two-thirds of the United States (Figure 9.18A). This dense, frigid air often brings record-breaking cold temperatures. In addition, recall from Chapter 8 that in the summer anticyclones can act to trap heat by preventing hot surface air from rising, thereby causing a heat wave.

Figure 9.18 Anticyclonic weather

A. A cold anticyclone associated with an outbreak of frigid arctic air impacts the eastern two-thirds of North America. Temperatures are shown in degrees Fahrenheit. **B.** Arctic air invades New England, bringing subzero temperatures and mostly clear skies.



Anticyclones generally produce clear skies and calm conditions, but in winter they can bring record-breaking cold temperatures, and in summer they can produce a heat wave.

Eye on the Atmosphere 9.3

This midlatitude cyclone swept across the central United States in October 2010. It produced strong wind gusts (up to 78 miles per hour), rain, hail, and snow, and it spawned 61 tornadoes. The cyclone set a record for the lowest measured pressure over land (not associated with a hurricane) in the continental United States: 28.21 inches of mercury. This pressure corresponds to that of a typical category 3 hurricane. Use the letters A–E, which represent various parts of the storm, to answer the following.

Apply What You Know

1. What part of the storm is dominated by a maritime tropical (mT) air mass?
2. Where is the area dominated by a continental polar (cP) air mass located?
3. Where did the strongest thunderstorms occur when this image was produced?
4. What area of the storm experienced the heaviest snowfall?
5. Where is the location of lowest pressure?

Occasionally, large anticyclones persist over a region for several days or even weeks. Once in place, these stagnant anticyclones block or redirect the migration of midlatitude cyclones and are called **blocking highs**. During these events, one section of the nation is kept dry for a week or more while another region remains continually under the influence of cyclonic storms. Such a situation prevailed during the summer of 2008, when a strong high-pressure system became anchored over the southern Great Plains and Ohio Valley, while abnormally low pressure was situated over the upper Midwest. The result was dry conditions in the southern Great Plains, contrasted with devastating flooding for the central and upper Mississippi Valley (see Severe & Hazardous Weather 9.1).

Severe & Hazardous Weather 9.1

The Midwest Flood of 2008

Floods are part of the natural behavior of streams. They are also among the most deadly and destructive of natural hazards. Flash floods in small valleys are frequently triggered by torrential rains that last just a few hours. By contrast, major regional floods in large river valleys often result from an extraordinary series of precipitation events over a broad region for an extended period. The Midwest flood of June 2008 is an example of the latter situation.

June was a very wet month across a significant part of this region, with numerous heavy rain events resulting in record flooding in Iowa, Wisconsin, Indiana, and Illinois. Rainfall totals were more than twice the monthly average in many places. Martinsville, Indiana, for example, reported 20.11 inches of rain for the month—an amount equal to about half its annual rainfall and more than double its previous record high for a single month.

> Rainfall totals were more than twice the monthly average in many places.

During the 2 months prior to the floods, the jet stream had been regularly dipping southward into the central United States, placing the favored storm track for rainy low-pressure centers over the Midwest. As a result, at least 65 locations in the Midwest set new June rainfall records, while more than 100 other stations had rainfall totals that ranked second to fifth on record. Prior to the heavy June rains, many of these stations experienced an exceptionally wet winter and spring. Soils that were already waterlogged provided no place for additional rain to go, forcing the flow across the surface and causing streams to rise.

> The June 2008 floods represented the costliest weather disaster in Indiana history.

The June 2008 floods represented the costliest weather disaster in Indiana history, and Iowa also suffered widespread losses, with 83 of its 99 counties declared disaster areas. Nine of Iowa's rivers were at or above previous record flood levels, and millions of acres of productive farmland (an estimated 16 percent of the state's total) were submerged. Residential and commercial areas were evacuated, mostly in Cedar Rapids, where more than 400 city blocks were underwater. The number of affected towns and rural areas throughout the Midwest was astonishing. Many riverside communities flooded when swollen streams breached levees built to protect the towns (Figure 9.A).

Figure 9.A Water rushes through a break in an artificial levee

During the record-breaking Midwestern floods of 2008, many levees could not withstand the force of the floodwaters.

Weather Safety

Flooding can be very dangerous. It is important to stay informed before, during, and after a flood. The American Red Cross also recommends the following:

- Get to high ground when flooding starts.
- Obey evacuation orders.
- Avoid walking, swimming, or driving in flooded areas.
- If driving on a flooded road with rapidly rising water, leave the vehicle and head to higher ground.

Apply What You Know

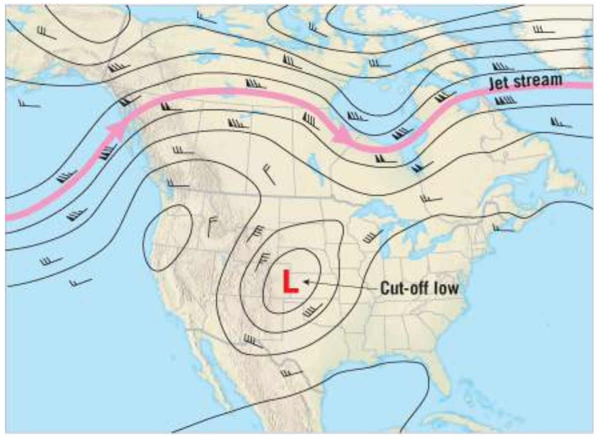
1. What is usually the cause of major regional floods in large river valleys?
2. How are flash floods normally triggered?

Strong blocking highs are also responsible for long periods of drought. One example is the devastating droughts that occurred in the Sahel from 1968 through 1974 and again in 2010. The Sahel includes the areas located south of Africa's Sahara Desert, which usually receive meager precipitation in summer when the intertropical convergence zone (ITCZ) moves northward. However, blocking highs during these periods prevented the ITCZ from moving sufficiently far poleward to bring much-needed precipitation.

Low-pressure systems can also generate a blocking pattern. These lows, called **cut-off lows**, are cut off from the west-to-east flow in the jet stream (Figure 9.19). Without a connection to the prevailing flow aloft, these lows remain over the same area for days, often producing dreary weather and large quantities of precipitation.

Figure 9.19 **Cut-off low pressure systems**

This cut-off low pressure system is literally cut off from the west-to-east flow in the jet stream. As a result, these systems can spin for days over the same area and are capable of producing large quantities of precipitation.



> Blocking highs and cut-off lows remain in place for long periods of time, affecting weather over a large region.

Concept Checks 9.7

- Describe the weather associated with a strong anticyclone that penetrates the southern tier of the United States in winter.
- What is a blocking high-pressure system?
- What type of weather does a cut-off low-pressure system typically bring to an area?

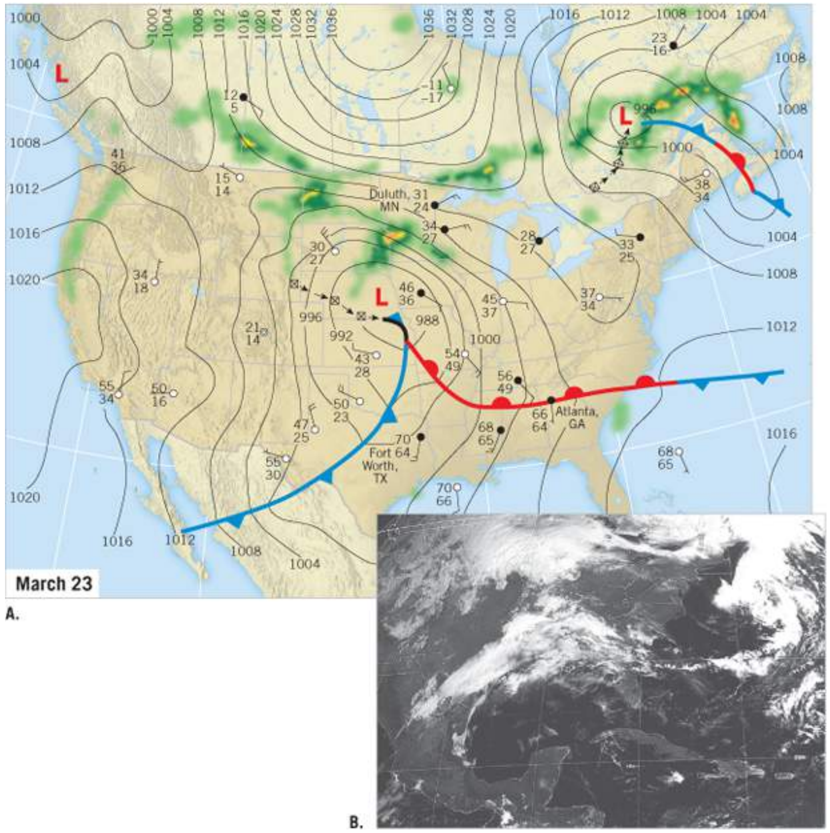
9.8 Case Study of a Midlatitude Cyclone

LO 8 Summarize the weather associated with a midlatitude cyclone over the north-central United States in winter.

To visualize the weather one might expect from a strong late-winter midlatitude cyclone, we will look at the evolution of a storm migrating across the United States in late March. This cyclone reached the west coast, near Seattle, Washington, on March 21. Like many other Pacific storms, this one rejuvenated east of the Rockies and moved eastward into the Plains. By the morning of March 23, it was centered near the Kansas–Nebraska border (Figure 9.20). At that time, the central pressure had reached 985 millibars, and the storm's well-developed cyclonic circulation exhibited a warm front and a cold front. Fort Worth, Texas, shown on the March 23 weather map in Figure 9.20, was under the influence of a warm, humid air mass and recorded a temperature of 70°F and a dew-point temperature of 64°F. Notice also in Figure 9.20 that winds in the warm sector were from the south and were overrunning cooler air situated north of the warm front. In contrast, the air behind the cold front was 20° to 40°F cooler than the air of the warm sector, and it was flowing from the northwest.

Figure 9.20 Weather on March 23

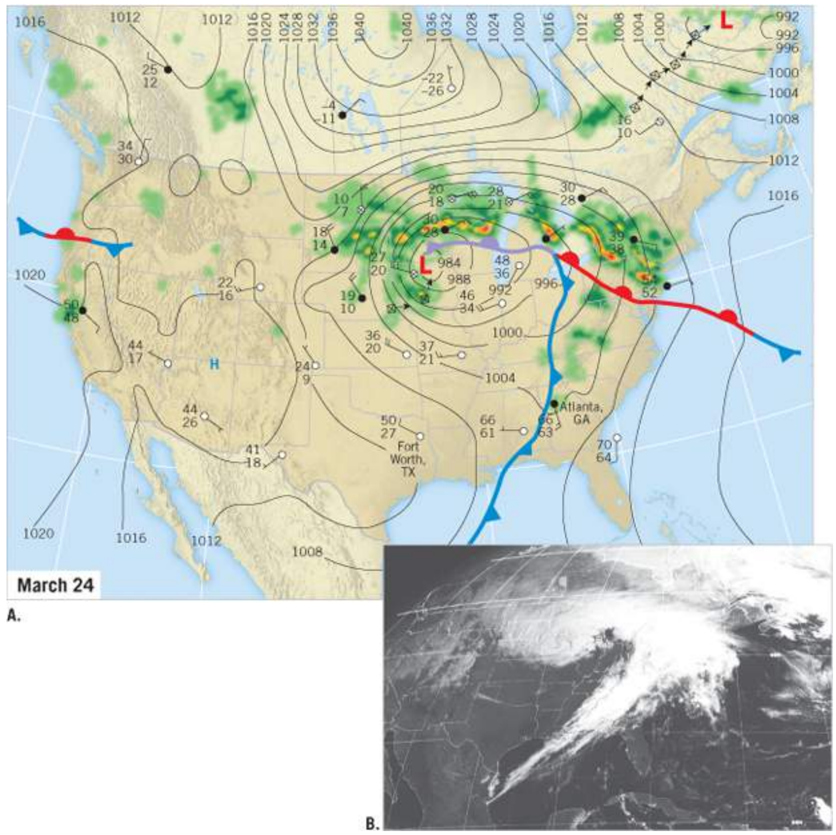
A. Surface weather map. **B.** Satellite image showing the cloud patterns.



During the next 24 hours, the storm curved slowly northward through Iowa, and the pressure deepened to 982 millibars (Figure 9.21). Although the storm center advanced slowly, the associated fronts moved vigorously toward the northeast. The northern sector of the cold front overtook the warm front and generated an occluded front (shown in purple), which was oriented nearly east–west by the morning of March 24 (Figure 9.21). The spacing of the isobars indicated a strong system that affected the circulation of the eastern two-thirds of the United States. A glance at the winds reveals a robust counterclockwise flow converging on the low.

Figure 9.21 **Weather on March 24**

A. Surface weather map. **B.** Satellite image showing the cloud patterns.



From March 23 to March 24, the storm produced one of the worst blizzards ever to hit the north-central states. In the Duluth–Superior area of Minnesota and Wisconsin, winds up to 81 miles per hour were measured, and speeds exceeding 100 miles per hour were estimated for the bridge connecting these cities. These winds blew 12 inches of snow into 10- to 15-foot drifts, and some roads were closed for 3 days (Figure 9.22).

Figure 9.22 Paralyzing blizzard strikes the north-central United States

> Weather conditions change rapidly and drastically as a midlatitude cyclone travels across the country.

While a winter storm was brewing in the northern tier of states, the cold front marched eastward from western Texas (on March 23) to the Atlantic Ocean (March 25). Throughout this region, the storm spawned numerous thunderstorms. High winds, hail, and lightning caused extensive damage, but the 19 tornadoes generated by the storm caused even greater death and destruction.

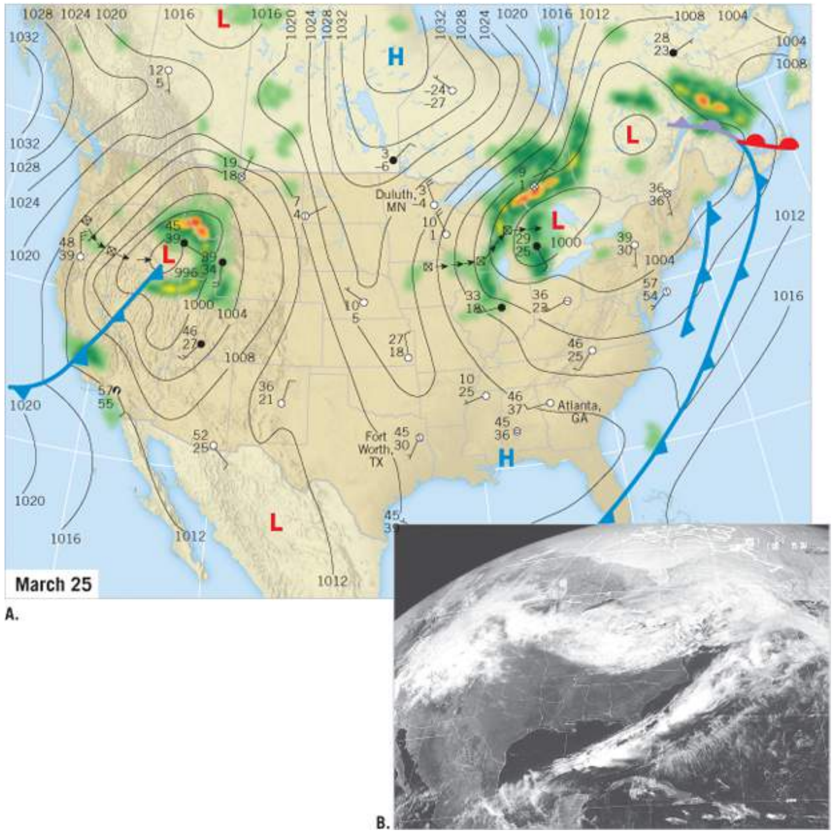
The path of the cold front can be easily traced from the reports of storm damage. By the evening of March 23, hail and wind damage were reported as far east as Mississippi and Tennessee. Early on the morning of March 24, golf ball–sized hail was reported in Selma, Alabama. About 6:30 a.m. that day, the "Governor's Tornado" struck Atlanta, Georgia, where the storm produced its worst destruction. The 12-mile path of the Governor's Tornado cut through an affluent residential area of Atlanta that included the governor's mansion (hence the name of the storm). The final damage (hail and a small tornado) was reported at 4:00 a.m. on March 25 in northeastern Florida. Thus, about 2 days and some 1200 kilometers after this cold front moved though Texas, it migrated out of the United States.

By the morning of March 24, cold polar air had penetrated deep into the United States behind the cold front (see Figure 9.21). Fort Worth, which just the day before had been in the warm sector, experienced cool northwest winds. Subfreezing temperatures were recorded in northern Oklahoma. Notice, however, that by March 25, Fort Worth was again experiencing a southerly flow. We can conclude that this was a result of the decaying cyclone that no longer dominated the circulation in the region.

Although the remnant low from this system, which was situated over the Great Lakes, generated some snow for the remainder of March 25, it had completely dissipated by the following day (Figure 9.23). You may have also noticed another cyclone moving in from the Pacific on March 25 as the earlier storm exited to the east. This new storm developed in a similar manner but was centered farther north. As you might guess, another blizzard hammered the Northern Plains, and a few tornadoes spun through Texas, Arkansas, and Kentucky, while precipitation dominated the weather in the central and eastern United States.

Figure 9.23 Weather on March 25

A. Surface weather map. **B.** Satellite image showing the cloud patterns.



You might have wondered . . .

Sometimes a major flood is described as a 100-year flood. What does that mean?

The phrase “100-year flood” is misleading because it implies that such an event happens only once every 100 years. In fact, an uncommonly big flood can happen any year. The phrase is really a statistical designation indicating that there is a 1-in-100 chance that a flood of a certain size will happen during any year. Perhaps a better term would be the “1-in-100-chances flood.” Many flood designations are reevaluated and changed over time as more data are collected or when a river basin is altered—for example, through dam construction or urban development—in a way that affects the flow of water.

Concept Checks 9.8

- Briefly describe the weather at Fort Worth, Texas, from March 23 through March 25, during the passage of this well-developed spring storm.
- How did the weather in the Duluth–Superior area of Minnesota and Wisconsin compare to that in the Fort Worth area during March 23–25?
- How did the weather in Atlanta, Georgia, change from March 23 to March 25?

Concepts in Review

9.1 Frontal Weather

LO 1 Compare and contrast typical weather associated with a warm front, cold front, occluded front, stationary front, and dryline.

Key Terms

front

overrunning

warm front

cold front

backdoor cold front

stationary front

occluded front

occlusion

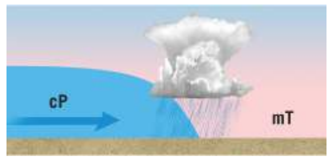
cold-type occluded front

warm-type occluded front

dryline

- Fronts are boundary surfaces that separate air masses of different densities, one usually warmer and more humid than the other. As one air mass moves into another, the warmer, less dense air mass is forced aloft in a process called overrunning.
- Temperature, humidity, pressure, wind speed and direction, cloud cover, and precipitation change drastically as warm or cold fronts pass.
- Warm fronts form when warmer air invades territory formerly occupied by cooler air. By contrast, cold fronts develop when cold air actively advances into a region occupied by warmer air.
- Stationary fronts form when the airflow on both sides of a front is neither toward the cold air mass nor toward the warm air mass.

- Occluded fronts most often form when a rapidly moving cold front overtakes a warm front.
- Drylines most often develop when dry, continental tropical (cT) air meets moist, maritime tropical (mT) air.



9.2 Midlatitude Cyclones and the Polar-Front Theory

LO 2 Outline the stages in the life cycle of a typical midlatitude cyclone.

Key Terms

midlatitude cyclone (middle-latitude cyclone)

polar-front theory (Norwegian cyclone model)

cyclogenesis

- The primary weather producer in the middle latitudes is the midlatitude, or middle-latitude, cyclone. Midlatitude cyclones have a cold front and a warm front extending from the central area of low pressure.
- According to the polar-front theory, when two air masses of different densities are moving parallel to the polar front and in opposite directions, cyclogenesis (cyclone formation) occurs, and the frontal surface takes on a wave shape.
- When a wave forms, warm air advances poleward, and cold air advances southward.
- Usually, the cold front advances faster than the warm front and lifts the warm front in a process known as occlusion. Eventually, the warm air around the low is forced aloft. At this point, the cyclone has exhausted its source of energy, and the once highly organized counterclockwise flow dissipates.

9.3 Flow Aloft and Cyclone Formation

LO 3 Relate divergence in airflow aloft to the development and intensification of a midlatitude cyclone at the surface.

- In cyclones, speed divergence and directional divergence east of the trough aloft supports the development of a low at the surface. Convergence aloft supports the development of a high at the surface.
- The westerly airflow aloft tends to steer these developing pressure systems in a general west-to-east direction.

9.4 A Modern View: The Conveyor Belt Model

LO 4 Explain the conveyor belt model of a midlatitude cyclone and describe the three interacting air streams on which it is based.

Key Terms

conveyor belt model

warm conveyor belt

cold conveyor belt

dry conveyor belt

- The modern view of cyclogenesis, called the conveyor belt model, provides a three-dimensional view of the airflow within a cyclonic storm. The warm and cold conveyor belts originate at the surface and ascend, and the dry conveyor belt originates aloft and descends.

9.5 Where Do Midlatitude Cyclones Form?

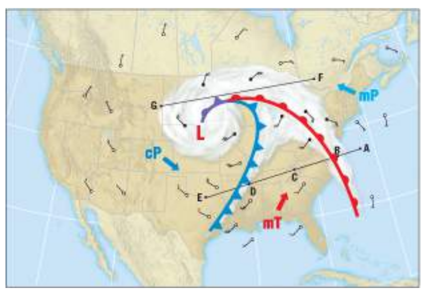
LO 5 Identify on a map the primary sites for the development of midlatitude cyclones affecting North America. Indicate typical paths for Alberta clippers, Colorado lows, Panhandle lows, Gulf lows, and nor'easters.

- Midlatitude cyclones tend to develop on the leeward sides of mountains and along coastal areas.
- Cyclones tend to move eastward or northeastward.

9.6 Idealized Weather of a Midlatitude Cyclone

LO 6 Describe the general weather conditions associated with the passage of a mature midlatitude cyclone.

- Different types of weather associated with a midlatitude cyclone can be expected, depending on your location relative to the storm's center of low pressure. South of the storm's center, you will encounter clouds and precipitation patterns associated with the passage of a warm front, followed by a cold front. North of the storm's center, you will encounter clouds and precipitation patterns associated with an occluded front.



9.7 Anticyclonic Weather and Atmospheric Blocking

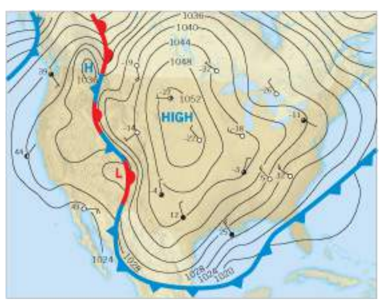
LO 7 Define a blocking high-pressure system and explain how it influences weather over the midlatitudes.

Key Terms

blocking high

cut-off low

- Because of the gradual subsidence within them, anticyclones tend to produce clear skies and generally calm conditions.
- Blocking highs can slow the movement of storm systems for weeks at a time, causing some areas to experience extreme amounts of precipitation while other areas may experience drought.



9.8 Case Study of a Midlatitude Cyclone

LO 8 Summarize the weather associated with a midlatitude cyclone over the north-central United States in winter.

- This section describes the effects of a spring cyclone on middle-latitude weather. Weather in Duluth, Fort Worth, and Atlanta each changed drastically as the cyclone moved eastward.

Exercises and Online Activities

Mastering Meteorology™

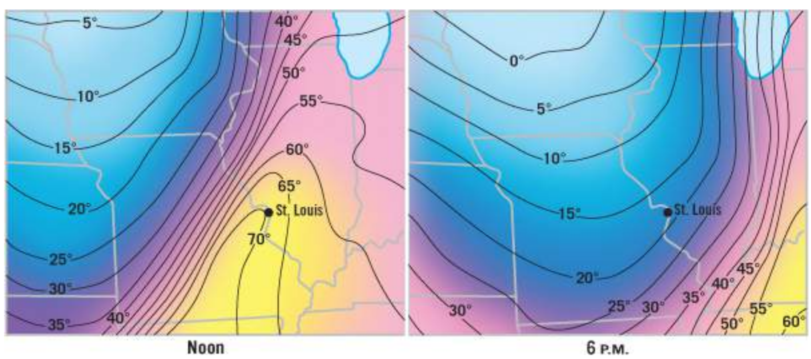
For instructor-assigned homework, test prep resources, and other learning materials, visit **Mastering Meteorology.**

Review Questions

1. Describe the weather ahead of as well as behind a warm front.
2. Describe the weather ahead of as well as behind a cold front.
3. Which type of front travels the fastest, and why?
4. Compare the weather of a cold-type occluded front with that of a warm-type occluded front.
5. Describe the weather ahead of as well as behind a dryline.
6. What symbol is used to denote each of the following on a weather map: warm front, cold front, occluded front, stationary front, and dryline?
7. Define *midlatitude cyclone*.
8. Where are warm fronts, cold fronts, and drylines generally located relative to the low? Explain their locations.
9. Why does a cyclone begin to dissipate when most of the warm air has been forced aloft?
10. Explain the role that convergence and divergence in the airflow aloft play in the development of a midlatitude cyclone.
11. Describe the life cycle of a cyclone based on the polar-front theory.
12. Describe the conveyor belt model, and explain how each belt moves in a midlatitude cyclone.
13. Compare and contrast the weather of a midlatitude cyclone that occurs poleward of the storm's center with a midlatitude cyclone that occurs equatorward of its center.
14. Briefly compare the weather of an anticyclone in the winter versus the summer.
15. Compare the airflow around a midlatitude cyclone in the Northern Hemisphere with an anticyclone in the same location.

Give It Some Thought

1. Sketch a vertical cross section (side view) of a cold front and a warm front, and include the following elements:
    a. Shape and slope of each type of front
    b. Air mass on both sides of each front
    c. Types of clouds typically associated with each front
    d. Type of rainfall associated with each front
    e. Characteristics of temperature and humidity found on both sides of each front
2. The accompanying diagrams show surface temperatures (in degrees Fahrenheit) for noon and 6:00 p.m. on January 29, 2008. On this day, an incredibly powerful weather front moved through Missouri and Illinois.



    a. What type of front passed through the Midwest?
    b. Describe how the temperature changed in St. Louis, Missouri, over the 6-hour period that began at noon and ended at 6:00 p.m.
    c. Describe the likely shift in wind direction in St. Louis during this time period.
3. The following questions refer to midlatitude cyclones and the frontal weather associated with them.
    a. Describe the weather several hours after the passage of a cold front. With what type of pressure system are these

weather conditions associated?

b. What is the source region for the mT air mass that produces most of the clouds and precipitation in the eastern two-thirds of the United States?

c. What type of severe weather would most concern a meteorologist when a stationary front is present over a region? (*Hint:* This severe weather type claims the most lives, on average, each year in the United States.)

4. Refer to the accompanying weather map and answer the following questions:

a. What is the probable wind direction at each of the lettered cities?

b. What air mass is likely to be influencing each city?

c. Identify the cold front, warm front, and occluded front.

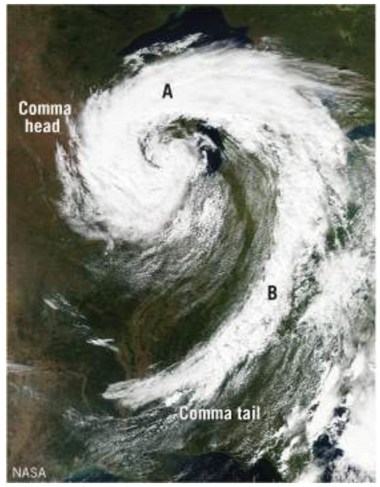
d. What is the barometric tendency at city A and at city C?

e. Which of the three cities is coldest? Which is warmest?

5. Explain the basis for the following weather proverb:

Rain long foretold, long last;
Short notice, soon past.

6. The accompanying satellite image shows the comma-shaped cloud pattern of a well-developed midlatitude cyclone over the United States in late winter.



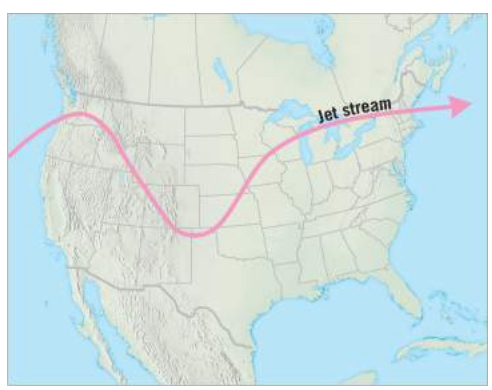
a. Describe the weather in northern Minnesota (A), located under the comma head of the winter storm.

b. What is the probable weather in eastern Alabama (B), which is located under the comma tail?

7. Why are occurrences of midlatitude cyclones less common over the United States in late summer than in winter and spring?

8. Write a statement explaining the relationship between the circulation around a surface low-pressure system and the flow aloft, using terms such as *ascending air*, *descending air*, *divergence*, and *convergence*.

9. The accompanying map shows the path aloft of the jet stream over the United States.



a. Where is the upper-air low (trough) located?

b. Where is the upper-air high (ridge) located?

c. In what region of the country or states would you expect the center of a low-pressure system to form?

d. In what region of the country or states would you expect a high-pressure system to be located?

By the Numbers

1. In the spring and summer, a warm moist (mT) air mass from the Gulf of Mexico occasionally collides with a warm dry (cT) air mass from the desert Southwest. These air masses meet over Texas, Oklahoma, and Kansas, producing a dryline. Thunderstorms that erupt along drylines can produce some of the most severe storms on the planet. When these two air masses meet, stormy weather is triggered when the less dense air mass overruns the denser air mass. Which of these two air masses is denser? Assume that the air temperature of the two air masses is the same. (*Hint:* Find the molecular weight of dry air [N_2 and O_2] with no water vapor [H_2O], and then compare that to what the molecular weight would be if about 4 percent of the N_2 and O_2 molecules were replaced by H_2O molecules.)
2. If you were located 400 kilometers ahead of the surface position of a typical warm front (with slope 1:200), how high would the frontal surface be above you?
3. Calculate how far ahead of a typical warm front you are when the first cirrus clouds begin to form. (*Hint:* Refer to Figure 5.1,, to find the minimum height range for high clouds.)
4. Refer to Table A, which provides weather observations for Champaign, Illinois, over a 3-day period as a midlatitude cyclone passed through the area. Answer the following questions, keeping in mind the general wind and temperature changes expected with the passage of fronts.
    a. During which day and at approximately what time did the warm front pass through Champaign?
    b. List two lines of evidence indicating that a warm front passed through Champaign.
    c. Explain the slight drop in temperature experienced between midnight and 6:00 a.m. on day 2.

d. On what day and at what time did the cold front pass through Champaign?

e. List two changes that indicate the passage of the cold front.

f. Did the thunderstorms in Champaign occur with the passage of the warm front or the cold front?

Table A Weather Data for Champaign, Illinois

	Temperature (°F)	Wind Direction	Weather and Precipitation
Day 1			
00:00	46	E	Partly cloudy
3:00 A.M.	46	ENE	Partly cloudy
6:00 A.M.	48	E	Overcast
9:00 A.M.	49	ESE	Drizzle
12:00 P.M.	52	ESE	Light rain
3:00 P.M.	53	SE	Rain
6:00 P.M.	68	SSW	Partly cloudy
9:00 P.M.	67	SW	Partly cloudy
Day 2			
00:00	66	SW	Partly cloudy
3:00 A.M.	64	SW	Mostly sunny
6:00 A.M.	63	SSW	Mostly sunny
9:00 A.M.	69	SW	Mostly sunny
12:00 P.M.	72	SSW	Mostly sunny
3:00 P.M.	76	SW	Mostly sunny
6:00 P.M.	74	SW	Cloudy
9:00 P.M.	64	W	Thunderstorm, gusty winds
Day 3			
00:00	52	WNW	Isolated thunderstorms
3:00 A.M.	48	WNW	Cloudy
6:00 A.M.	42	NW	Partly cloudy
9:00 A.M.	39	NW	Mostly sunny
12:00 P.M.	38	NW	Sunny
3:00 P.M.	40	NW	Sunny
6:00 P.M.	42	NW	Sunny
9:00 P.M.	40	NW	Sunny

Beyond the Textbook

Reading Forecast Maps

Forecast maps are used to predict upcoming weather conditions and hazards. Go to the National Weather Service page at http://www.wpc.ncep.noaa.gov/national_forecast/natfcst.php?day=1 to display the current forecast map.

1. Which of the fronts discussed in this chapter are shown on the forecast map?
2. Select a front that has precipitation associated with it by locating areas found within orange colored dashed lines. Areas of potentially hazardous conditions are marked with brightly colored lines. Describe the type of precipitation associated with that front and its location relative to the front.
3. Does the precipitation pattern near this front match the type of precipitation you would expect to be associated with this type of front? Explain.
4. Where are the midlatitude cyclones (low-pressure "**L**" areas having fronts) located on the map?
5. Select a prominent midlatitude cyclone, and note its location. Compare and contrast the midlatitude cyclone to the idealized cyclone shown in Figure 9.16. Be sure to compare the types of fronts, frontal orientations, and any precipitation.
6. Click on the Tomorrow's Forecast tab. In what general direction is the cyclone you selected predicted to move from today to tomorrow? Is that path similar to or different from the path of the idealized cyclone shown in Figure 9.8? Explain.
7. Describe how the precipitation pattern associated with this cyclone is expected to change during the next 24 hours.
8. Click on the Day 3 Forecast tab. In what general direction is this cyclone expected to move from today's location to that of day 3?

9. Describe the precipitation pattern associated with this cyclone on the Day 3 Forecast map. Based mainly on changes in the precipitation pattern over this 2-day period, is the storm expected to increase or decrease in strength? Explain your reasoning.

Chapter 10 Thunderstorms and Tornadoes

EF-5 Tornado near Dodge City, Kansas, May 24, 2016.

Focus on Concepts

Each statement represents the primary learning objective for the corresponding major heading within the chapter. After you complete the chapter, you should be able to:

1. List the three basic requirements for the formation of an ordinary thunderstorm, and describe the additional component required for a thunderstorm to become severe (10.1).
2. Sketch and label simple diagrams that illustrate the three stages of an ordinary thunderstorm (10.2).
3. List the characteristics of a severe thunderstorm and distinguish among squall lines, mesoscale convective complexes, and supercell thunderstorms (10.3).
4. Explain what causes lightning and thunder (10.4).
5. Describe the structure and basic characteristics of tornadoes (10.5).
6. Summarize the atmospheric conditions and locations that are favorable to the formation of tornadoes (10.6).
7. Describe tornado intensity. Distinguish between a tornado watch and a tornado warning, and discuss the role of Doppler radar in the warning process (10.7).

This chapter and Chapter 11 focus on severe and hazardous weather. In this chapter we examine the severe local weather produced in association with cumulonimbus clouds—namely, thunderstorms and tornadoes. In the next chapter, we will turn to the large tropical cyclones we call hurricanes.

Severe weather outbreaks are more fascinating than ordinary weather phenomena. The lightning display generated by a thunderstorm can be a spectacular event that elicits both awe and fear. Of course, tornadoes and hurricanes also attract a great deal of much-deserved attention. A single tornado outbreak or hurricane can cause billions of dollars in property damage as well as many deaths.

10.1 Thunderstorms

LO 1 List the three basic requirements for the formation of an ordinary thunderstorm, and describe the additional component required for a thunderstorm to become severe.

Almost everyone has observed small-scale phenomena that result from the vertical movements of relatively warm, unstable air. Perhaps you have seen a dust devil over an open field on a hot day, whirling its dusty load to great heights, or watched a bird glide effortlessly skyward on an invisible thermal (rising parcel of air). These examples illustrate the dynamic thermal instability of an air mass in which *thunderstorms* develop. As the name implies, a **thunderstorm** is a storm that generates lightning and thunder. It may also produce gusty winds, heavy rain, hail, and possibly a tornado. A thunderstorm may be a single, isolated cumulonimbus cloud that affects only a small area, or it may be associated with clusters of cumulonimbus clouds covering a very large area.

Conditions for Thunderstorm Development

Thunderstorms are convective cumulonimbus clouds that form when warm, humid air is lifted in a *conditionally unstable environment* (see Chapter 4 for a discussion of atmospheric stability). Warm maritime air may have moved inland or remains available from the previous day's thunderstorms. To trigger a thunderstorm, moist air must be lifted to the level of free convection (LFC), at which point the air becomes buoyant enough to rise on its own. Recall that rising air gets it buoyancy from the *latent heat* released when water vapor condenses to form water droplets or ice crystals. As long as the rising air remains warmer than the surrounding environment, it will continue its upward journey. However, because of the average temperature profile of the atmosphere, the rising air begins to lose its buoyancy once it reaches the tropopause. (Recall from Chapter 1 that the tropopause is located at the base of the stratosphere, which serves as a *temperature inversion* that restricts vertical air movement.) As a result, mature thunderstorm (cumulonimbus) clouds tend to flatten out near the tropopause (Figure 10.1). Like many other cloud types, thunderstorm clouds also have relatively flat bottoms that begin at the height of the lifting condensation level (LCL).

Figure 10.1 Cumulonimbus cloud

This cumulonimbus cloud became a towering August thunderstorm over central Illinois.

Various mechanisms can trigger the upward air movement needed to create thunderstorm clouds. Daytime heating significantly contributes to the formation of relatively small *single-cell thunderstorms*, also known as *ordinary cell thunderstorms* (Figure 10.1). These storms, usually short-lived and seldom producing destructive winds or hail, commonly form *within* maritime tropical (mT) air masses.

Most ordinary thunderstorms form on hot summer days as the result of differential heating of Earth's surface—which produces pockets of air that are warmer and less dense than the surrounding air. These rising parcels of air can be quite small, perhaps the diameter of a few city blocks. If a parcel is large and buoyant enough, it can rise to form a puffy cumulonimbus cloud and trigger a thunderstorm. Surface convergence, a cool sea breeze blowing onto a warm landmass, and orographic lifting along a mountain slope are common lifting mechanisms responsible for thunderstorm development.

> Formation of ordinary thunderstorms require moisture, instability, and a lifting mechanism.

By contrast, severe thunderstorms not only benefit from uneven surface heating, but also are most often associated with frontal lifting of warm, moist air. In addition to the ascent of moist air in a conditionally unstable environment, severe thunderstorms usually require one additional component: wind shear. *Wind shear* is the change in wind speed and/or direction with increasing height above the surface. Severe thunderstorms may produce high winds, damaging hail, flash floods, and tornadoes. We will examine both ordinary and severe thunderstorms in more detail later in this chapter.

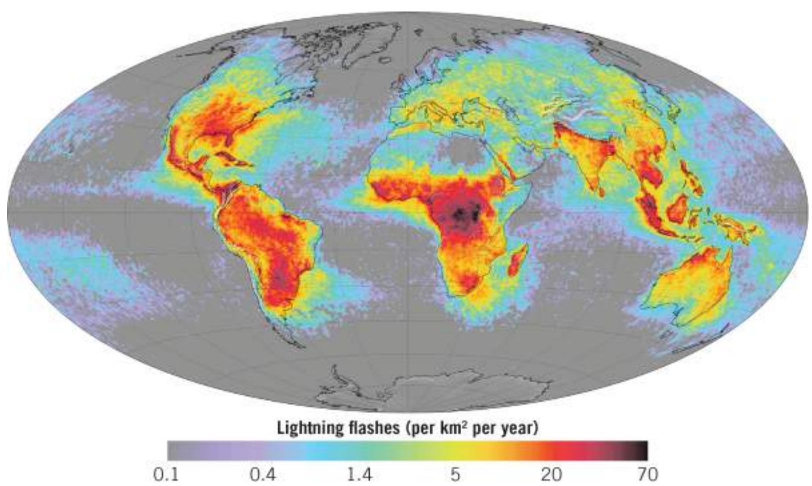
> In addition to ascending moist air in a conditionally unstable environment, severe thunderstorms usually require one additional component: wind shear.

Distribution and Frequency

Globally, at any given time, an estimated 2000 thunderstorms are in progress. About 45,000 thunderstorms take place each day, and more than 16 million occur annually around the world. Lightning from these storms strikes Earth 100 times each second. As we would expect, the greatest proportion of these storms and lightning strikes occur where warm air, abundant moisture, and instability are present (Figure 10.2). Thus, thunderstorms occur in many tropical areas year-round. In the middle latitudes, these storms are largely warm-season phenomena and become less common in locations farther from the equator.

Figure 10.2 World distribution of lightning

Data from space-based optical sensors show the worldwide distribution of lightning.



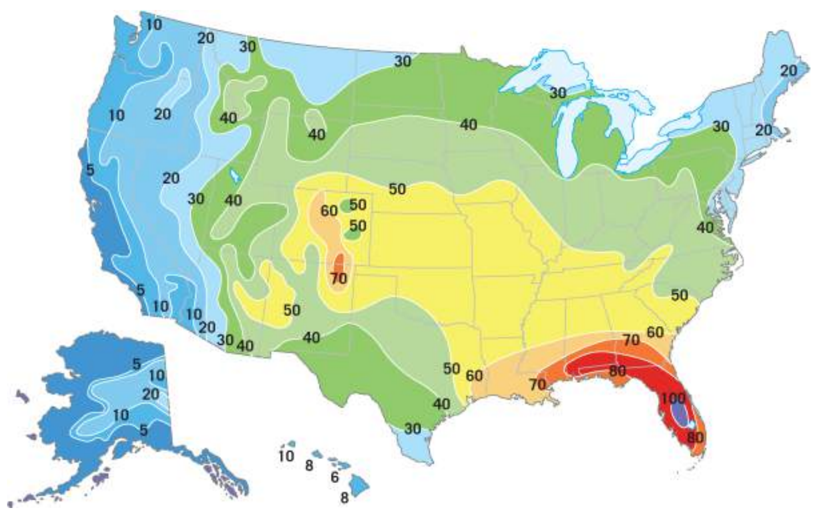
> Thunderstorms occur year-round in tropical regions and during the warmer months in the midlatitudes.

Annually the United States experiences about 100,000 thunderstorms, about 10 percent of which are severe. Figure 10.3 shows that thunderstorms are most frequent in the maritime tropical (mT) air of

Florida and the eastern Gulf Coast region, where activity is recorded between 70 and 100 days each year. The region of gradually sloping terrain on the east side of the Rockies in Colorado and New Mexico ranks second—there, thunderstorms occur 60 to 70 days annually. By contrast, the western margin of the United States has minimal thunderstorm activity because the air is rarely unstable. Likewise, in the very northern tier of states and Canada, warm, moist, unstable mT air penetrates less often.

Figure 10.3 **Average number of days per year with thunderstorms**

Regions where mT air resides or penetrates receive the most thunderstorms, whereas cooler and dryer regions receive far fewer thunderstorms.



Concept Checks 10.1

- What are the primary requirements for the formation of ordinary thunderstorms? What additional component is necessary for a thunderstorm to become severe?
- Globally, where would you expect thunderstorms to be most common? Where in the United States?

10.2 Ordinary Cell Thunderstorms

LO 2 Sketch and label simple diagrams that illustrate the three stages of an ordinary thunderstorm.

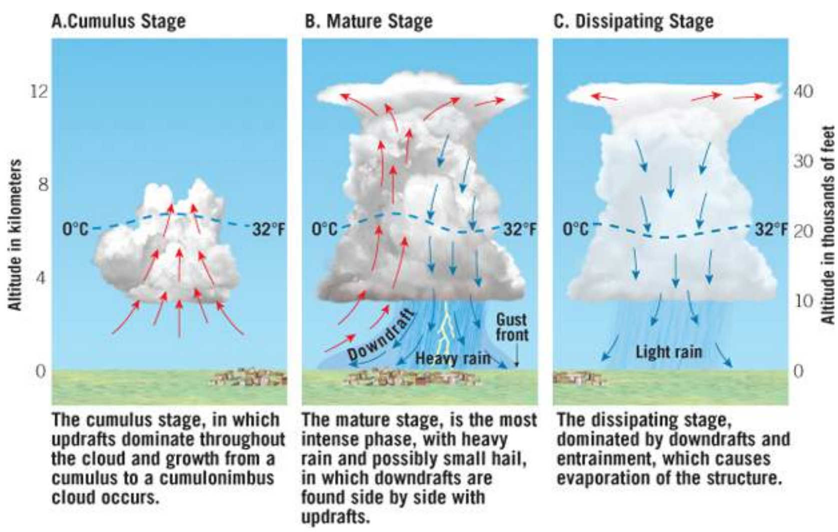
In the United States, **ordinary cell thunderstorms**, or simply **ordinary thunderstorms**, frequently occur in maritime tropical air that moves northward from the Gulf of Mexico. Ordinary thunderstorms are also known as **air-mass thunderstorms** because they usually form in warm, humid mT air masses. These large air masses contain abundant moisture in their lower levels, which can be rendered unstable when heated from below or when the air is lifted along a boundary between air masses of different densities. Surface convergence can also cause air to rise, including situations where air over a comparatively smooth water surface moves onto an irregular land surface and slows as a result of friction.

Ordinary thunderstorms occur most frequently in spring and summer when mT air is warmed from below by solar heating of the land surface. They also tend to occur in midafternoon, when surface temperatures are highest. Because local differences in surface heating influence their growth, ordinary thunderstorms occur as scattered, isolated cells (cumulonimbus clouds) rather than in organized bands or other configurations.

Stages of Development

Ordinary thunderstorms are single-cell events that are short-lived, sometimes lasting less than an hour. They also have fairly predictable life cycles that begin with a period dominated by updrafts. This is followed by a period of moderate to heavy precipitation, which produces a downdraft that eventually cuts off the updraft. Without a supply of moisture, the storm quickly dissipates. The three stages in the life cycle of an ordinary cell thunderstorm are depicted in Figure 10.4.

Smartfigure 10.4 **Stages in the development of an ordinary cell thunderstorm**



Watch **SmartFigure: Thunderstorms**

Cumulus Stage

Recall that an ordinary thunderstorm is largely a product of uneven heating of the surface often aided by converging surface winds, which leads to rising currents of air that ultimately produce a cumulonimbus cloud. At first, the buoyant thermals produce fair-weather cumulus clouds that may exist for just minutes before evaporating into the drier air aloft. This initial cumulus development is important because it moves moisture from the surface to greater heights. Ultimately, the air aloft becomes sufficiently humid that newly forming cumulus clouds do not evaporate but instead continue to grow vertically (Figure 10.5).

Figure 10.5 Cumulus development

Buoyant thermals produce fair-weather cumulus clouds that soon evaporate into the surrounding air, making the air more humid. As this process of cumulus development and evaporation continues, the air eventually becomes sufficiently humid so that newly forming clouds do not evaporate but continue to grow.

> The cumulus stage is dominated by an updraft that lifts moisture from near the surface upward.

The development of a cumulonimbus tower requires a continuous supply of moist air. The release of latent heat allows each new surge of warm air to rise higher than the last, adding to the cloud's height. This phase in the development of a thunderstorm, called the **cumulus stage**, is dominated by updrafts (Figure 10.4A).

Once the cloud passes beyond the freezing level, the Bergeron process (see Chapter 5) begins producing precipitation. In the towering cumulus stage, the updrafts suspend the growing raindrops until the point when the raindrops become too "heavy" for the updrafts to support. The falling precipitation causes drag on the air and initiates a downdraft.

The downdraft is further aided by the influx of cool, dry air aloft, a process termed **entrainment**. This process intensifies the downdraft because the air that surrounds the cloud aloft is cool and dry, and therefore dense. The entrainment of dry air also causes some of the falling precipitation to evaporate (a cooling process), thereby further cooling the air within the downdraft.

Mature Stage

As a downdraft leaves the base of a cloud, it carries precipitation with it, marking the beginning of the cloud's **mature stage**. At the surface, the cool downdrafts spread laterally and can be felt as sharp, cool gusts at the surface before the precipitation reaches the ground. During the mature stage, updrafts exist along with downdrafts and continue to enlarge the cloud. When the cloud grows to the top of the unstable region, often located at the tropopause, the updrafts spread laterally and produce the cloud's characteristic anvil top (Figure 10.4B). The mature stage is the most active period of a thunderstorm. Gusty winds, lightning, heavy precipitation, and, sometimes, small hail are common. Occasionally, a **microburst**—a sudden, powerful downward burst of air—is produced by a strong downdraft, impacting Earth's surface with such force that it produces surface winds in excess of 60 miles per hour (see Severe & Hazardous Weather 10.1).

Severe & Hazardous Weather 10.1

Downbursts (Microbursts)

Downbursts are strong localized zones of sinking air that originate in the lower part of some cumulus and cumulonimbus clouds. Downbursts are different from typical thunderstorm downdrafts in that they are more intense and concentrated over smaller areas (Figure 10.A). Their small horizontal dimension, usually less than 4 kilometers (2.5 miles), is why the term *microburst* is often used. When a downburst reaches the ground, air spreads out in all directions, like a jet of water from a faucet splashing in a sink. Within minutes the downburst dissipates, while the outflow of air at the ground continues to expand. The straight-line winds from a downburst can exceed 160 kilometers (100 miles) per hour and can cause damage equivalent to that of a weak tornado.

Figure 10.A Dangerous downburst

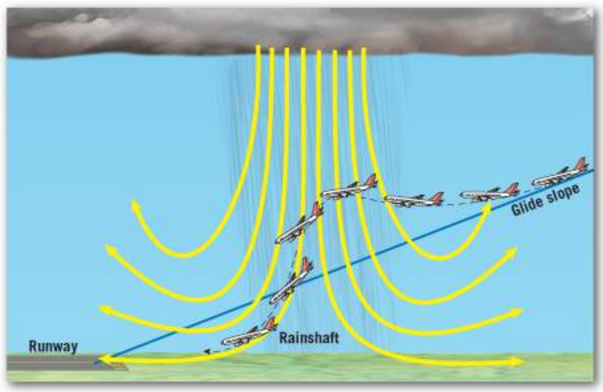
The rain shaft extending downward from a cumulonimbus cloud identifies a powerful downburst near Denver's Stapleton Airport.

The acceleration of air in a downburst occurs when evaporating raindrops cool the air. Remember that the colder the air, the denser it is, and the denser the air, the faster it will "fall." A second mechanism that contributes to downbursts is the drag of falling precipitation—the force of millions of falling drops can be substantial.

The violent winds of a downburst can be destructive, but they are extremely hazardous to aircraft, especially during takeoff and landing, when planes are nearest the ground. Imagine an aircraft attempting to land and being confronted by a downburst, as shown in Figure 10.B. As the airplane flies into the downburst, it initially encounters a strong headwind, which tends to carry it upward. To reduce the lift, the pilot points the nose of the aircraft downward. Then, seconds later, a tailwind is encountered. Now, because the wind is moving with the airplane, the amount of air flowing over the wings and providing lift is dramatically reduced, causing the craft to suddenly lose altitude and possibly crash. This serious aviation hazard has been reduced significantly because systems to detect the wind shifts associated with downbursts have been deployed at major airports.

Figure 10.B Airport hazard

The arrows in this sketch represent the downward and outward movement of air in a downburst. An airplane passing through a downburst as it attempts to land initially experiences a strong headwind and lift. That is followed by an abrupt descent, caused by the downward motion of air, and a rapid loss of air speed.



> Downbursts are extremely hazardous to aircraft, especially during takeoff and landing.

Weather Safety

While downbursts are dangerous to aircraft, they can also be hazardous to people on the ground. Downbursts can produce winds as strong as a tornado, blowing down trees and power lines. If the forecast calls for a downburst, you should:

- Take shelter in a sturdy building.
- Stay away from windows.

Apply What You Know

1. What is another name for a downburst?
2. List two factors that contribute to the formation of a downburst.

> The mature stage is the most active period of a thunderstorm and is characterized by rain and both an updraft and a downdraft.

Dissipating Stage

When precipitation starts to fall, the drag of the raindrops begins to strengthen and enlarge the area of downdraft, which enables even more rain to fall. Essentially, the rain turns the updraft into a downdraft, which in turn causes the storm to be cut off from its supply of rising moist air. Eventually, the downdrafts dominate throughout the cloud and initiate the **dissipating stage** (Figure 10.4C). The cooling effect of falling precipitation and the influx of colder air aloft mark the end of thunderstorm activity. Without a supply of moisture from updrafts, the cloud will soon evaporate. The entire lifecycle of ordinary thunderstorm lasts about an hour.

> The dissipating stage begins when the downdraft completely cuts off the updraft.

Multicell Thunderstorms

Some thunderstorms consist of a single cell that proceeds through its life cycle and dissipates, without any accompanying cells. In other circumstances, numerous cells in various stages of development are clustered together; these are called **multicell thunderstorms**. Each cell of a multicell thunderstorm behaves like an ordinary single-cell thunderstorm. When a cell forms, the upper level winds carry it downstream (downwind), and a new cell begins to grow in its path, usually west or southwest of the cluster in the middle latitudes. The formation of a trailing storm is often triggered by lifting caused by the downdraft from the initial storm as it reaches maturity.

The speed at which a cluster of thunderstorms move greatly influences the amount of precipitation an area in the path of the storms will receive. In addition, when one or more newly formed cells moves directly over the path of the initial cell, the total rainfall over a small area can be considerable and lead to flash flooding. Multicell thunderstorms tend to be more destructive than single cell storms, but less destructive than severe supercell thunderstorms.

Occurrence

Mountainous regions, such as the Rockies in the West and the Appalachians in the East, experience a greater number of ordinary thunderstorms than do the Plains states. The air near the mountain slope is heated more intensely than air at the same elevation over the adjacent lowlands. A general upslope movement then develops over the course of the day and can sometimes generate thunderstorm cells. These cells may remain almost stationary, sometimes causing dangerous flooding at lower elevations.

Although high surface temperatures promote the growth of ordinary thunderstorms, many thunderstorms are not generated solely by surface heating. For example, many of Florida’s thunderstorms are triggered by the convergence associated with sea-to-land airflow (see Figure 4.20,). Many thunderstorms that form over the eastern two-thirds of the United States occur as part of the general convergence and frontal lifting that accompany passing midlatitude cyclones. Near the equator, thunderstorms commonly form in association with the convergence along the equatorial low and intertropical convergence zone. Most, but not all, multicell thunderstorms are *not* severe, and their life cycles are similar to the three-stage model described for ordinary thunderstorms.

Concept Checks 10.2

- During what seasons and at what time of day is ordinary thunderstorm activity greatest? Why?
- Why do entrainment and evaporation of raindrops intensify thunderstorm downdrafts?
- Summarize the three stages of an ordinary thunderstorm.

10.3 Severe Thunderstorms

LO 3 List the characteristics of a severe thunderstorm and distinguish among squall lines, mesoscale convective complexes, and supercell thunderstorms.

Severe thunderstorms are capable of producing heavy downpours and flash floods as well as strong, gusty straight-line winds; large hail; frequent lightning; and perhaps a tornado (see Severe & Hazardous Weather 10.2). For the National Weather Service (NWS) to classify a thunderstorm as *severe*, the storm must have winds in excess of 93 kilometers (58 miles) per hour, or produce hailstones larger than 2.5 centimeters (1 inch) in diameter, or generate a tornado. Of the estimated 100,000 thunderstorms that occur annually in the United States, about 10 percent (10,000 storms) reach severe status.

Severe & Hazardous Weather 10.2

Flash Floods

Tornadoes and hurricanes are nature’s most awesome storms. Yet these dreaded events are not responsible for the greatest number of storm-related deaths. That distinction goes to floods.

Major regional floods in large river valleys often result from an extraordinary series of precipitation events over a broad region for an extended time span. Examples of such floods are discussed in Chapter 9. By contrast, just an hour or two of intense thunderstorm activity can trigger flash floods in small valleys. Such situations are described here.

Flash floods are localized floods of great volume and short duration. The rapidly rising surge of water usually occurs with little advance warning and can destroy roads, bridges, homes, and other substantial structures (Figure 10.C). The amount of water flowing in a channel quickly reaches a maximum and then diminishes rapidly. Flood flows often contain large quantities of sediment and debris as they sweep channels clean.

Figure 10.C

A firefighter carries a woman from her car during a flash flood, February 17, 2017, Sun Valley California.

Several factors influence flash flooding. Among them are rainfall intensity and duration, surface conditions, and topography. Frequently, flash floods result from the torrential rains associated with a slow-moving severe thunderstorm or take place when a series of thunderstorms repeatedly pass over the same location. Sometimes they are triggered by heavy rains from hurricanes and tropical storms.

> Just an hour or two of intense thunderstorm activity can trigger flash floods in small valleys.

Flash floods are particularly common in mountainous terrain, where steep slopes can quickly channel runoff into narrow valleys. The hazard is most acute when the soil is already nearly saturated from earlier rains or consists of impermeable materials. Urban areas are also highly susceptible to flash floods because a high percentage of the surface area is composed of impervious roofs, streets, and parking lots, where runoff is very rapid.

Weather Safety

Why do so many people perish in flash floods? Aside from the surprise factor, humans do not understand the power of moving water. Just 15 centimeters (6 inches) of fast-moving floodwaters can knock you off your feet. Most automobiles can be swept away in only 0.6 meters (2 feet) of water (Figure 10.C). More than half of all U.S. flash-flood fatalities are auto related. Safety suggestions during a flood warning include the following:

- Never attempt to drive on a flooded road.
- If your vehicle stalls, abandon it immediately and get to higher ground.

Apply What You Know

1. List at least three factors that influence flash flooding.
2. When rural areas become urbanized, the chances of flash floods increase. Explain why.

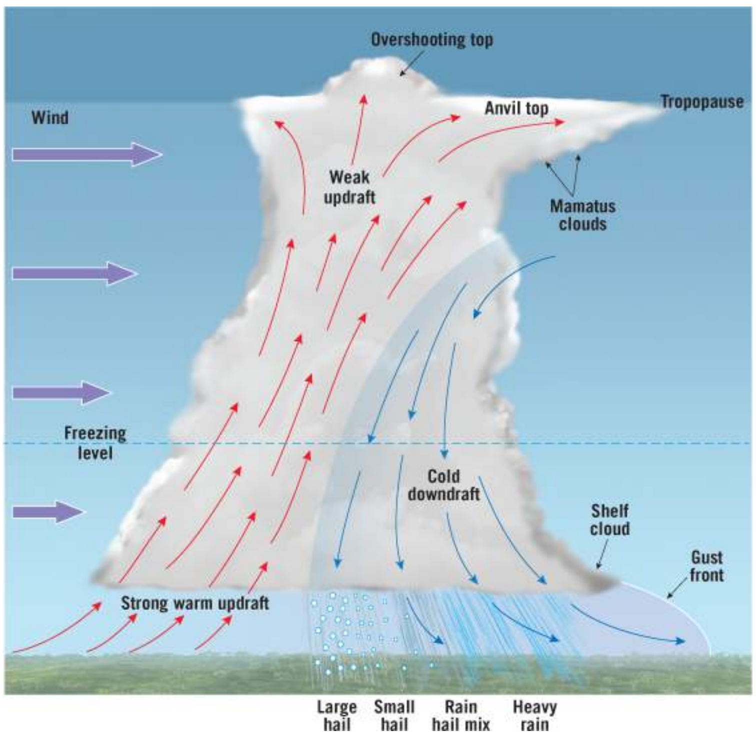
As you learned in the preceding section, ordinary thunderstorms are localized, relatively short-lived phenomena that dissipate after a brief, well-defined life cycle. They extinguish themselves because downdrafts cut off the supply of moisture needed to maintain the storm. For this reason, ordinary thunderstorms seldom produce severe weather. By contrast, severe thunderstorms do not quickly dissipate but may instead remain active for hours.

> For a thunderstorm to be considered *severe* by the National Weather Service, it must produce damaging winds, hail larger than 1 inch, and/or a tornado.

Why do some thunderstorms persist for many hours? A key factor is the existence of strong vertical **wind shear**—that is, relatively abrupt changes in wind direction and/or wind speed with increasing height above Earth's surface. When such conditions prevail, the updrafts that provide the storm with moisture do not remain vertical but become *tilted*. Because of this, precipitation that forms high in the cloud does not fall into the updraft, as occurs in ordinary thunderstorms. This allows the updraft to continually supply the developing cloud with a source of moisture and to continue to build upward (Figure 10.6). Sometimes the updrafts are sufficiently strong that the cloud top is able to push its way into the stable lower stratosphere, forming a structure called an **overshooting top**.

Figure 10.6 **Diagram of a well-developed severe thunderstorm**

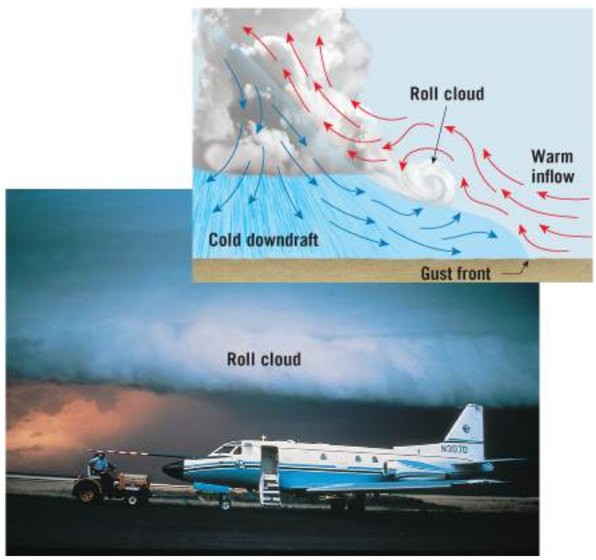
This cumulonimbus cloud is characterized by updrafts, downdrafts, and an overshooting top. Precipitation forming in the tilted updraft falls into the downdraft. Beneath the cloud, the denser cool air of the downdraft spreads out along the ground. The leading edge of the outflowing downdraft acts to wedge moist surface air up into the cloud. Eventually the outflow boundary may become a gust front that initiates new cumulonimbus development.



Beneath the cumulonimbus tower, where downdrafts reach the surface, the denser cool air spreads out along the ground. The leading edge of this downdraft, or *outflow boundary*, is called a **gust front**. By examining Figure 10.7, you can see that the gust front acts as a "mini cold front" as it advances into the warm air that surrounds the storm. As the gust front moves across the ground, this very turbulent air sometimes picks up loose dust and soil, making the advancing boundary visible. The gust front's advance can also provide the lift needed for the formation of new thunderstorms many kilometers away from the initial cumulonimbus clouds. As the gust front passes, the air temperature sharply drops, and wind speed abruptly increases. The winds behind the gust front are termed **straight-line winds** to differentiate them from the rotating winds of a tornado. According to the NWS, wind speeds of 50–60 miles an hour are considered damaging and are capable of downing powerlines, uprooting trees, and damaging mobile homes.

Figure 10.7 Roll cloud

This roll cloud (shelf cloud) at Miles City, Montana, was produced along a gust front between an updraft and a downdraft.



Frequently, a roll cloud or shelf cloud (also called *arcus clouds*) form along the leading edge of the parent cloud, above the gust front. A **roll cloud**, shown in Figure 10.7, is a horizontal tube-shaped cloud that is often detached from the parent cloud. Roll clouds, which may appear to be rolling about a horizontal axis, most often form between the areas of cold downdraft and warm inflow of a severe thunderstorm. **Shelf clouds**, which form in a similar environment, are low, horizontal wedge-shaped clouds (Figure 10.8). This ominous-looking wall of clouds, which is usually accompanied by the strong, cold winds of a gust front, is often mistaken for a *wall cloud*—the cloud from which funnel clouds may emerge. However, shelf clouds usually form at the *leading edge* of severe thunderstorms, whereas wall clouds usually appear at the *rear* of the storm.

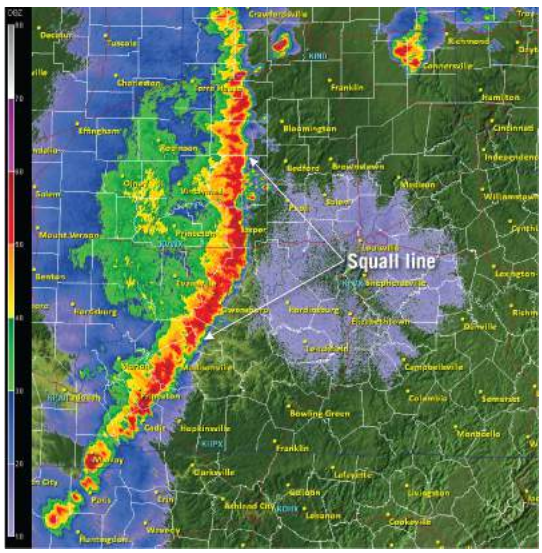
Figure 10.8 Ominous shelf cloud

Shelf cloud of a powerful thunderstorm moves over a rural home in eastern Nebraska.

Squall Lines

A **squall line** is a relatively narrow band of thunderstorms, some of which may be severe. The linear band of cumulonimbus development might stretch for 500 kilometers (300 miles) or more and consist of many individual cells in various stages of development. On a radar image, a squall line often looks like a line with bulges (Figure 10.9). An average squall line can last 10 hours or more, and some have been known to remain active for more than a day. Sometimes the approach of a squall line is preceded by an ominous-looking shelf cloud (Figure 10.8).

Figure 10.9 Radar view of a strong squall line

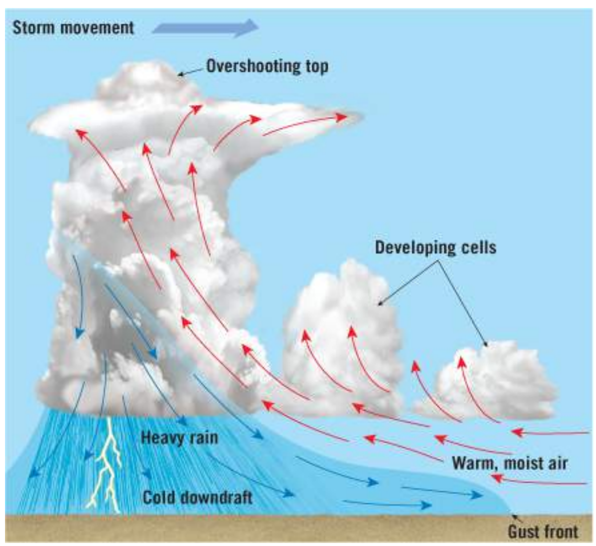


> Squall lines are narrow bands of storms that produce heavy rain and strong winds.

Most squall lines are produced by forceful lifting along or ahead of a cold front or dryline (see Chapter 9). As the frontal surface advances, it lifts warm, humid air, creating an updraft along the leading edge of the storm. A downdraft eventually develops upwind (in the rear of the storm), which generates a strong gust front that can extend beyond the leading edge of the thunderstorm (Figure 10.10). As the storm continues to evolve, new cells form—generally south and east of the old cells. These thunderstorm cells can sustain themselves by producing their own lift due to the outflow of cold air associated with the gust front. As long as there is warm, moist air and instability ahead of a squall line, the storm will continue to propagate. Squall lines can even outrun the cold front or dryline that produced them.

Figure 10.10 One cell in a squall line of strong thunderstorms

The outflow boundary (gust front) often triggers development of a new cumulonimbus cell.



Small hail or weak tornadoes may be associated with the squall line, but the most common weather is strong straight-line winds, heavy rain, and abundant lightning. When a squall line stalls or moves slowly, it often produces flooding because it is situated over the same location for an extended time. By contrast, convective clouds that are rapidly advancing sometimes produce widespread long-lived, straight-line winds that exceed 50 knots (58 miles per hour) called *derechos*. These winds can reach hurricane speeds and damage areas more than 400 kilometers (250 miles) in width.

You might have wondered . . .

What would it be like inside a towering cumulonimbus cloud?

The words *violent* and *dangerous* come to mind! A German paragliding champion was pulled into an erupting thunderstorm near Tamworth, New South Wales, Australia, and blacked out.* Updrafts lofted her to 32,600 feet, covered her with ice, and pelted her with hailstones. She finally regained consciousness around 22,600 feet. Her GPS equipment and a computer tracked her movements as the storm carried her away. Shaking vigorously and with lightning all around, she managed to slowly descend and eventually land 40 miles from where she started.

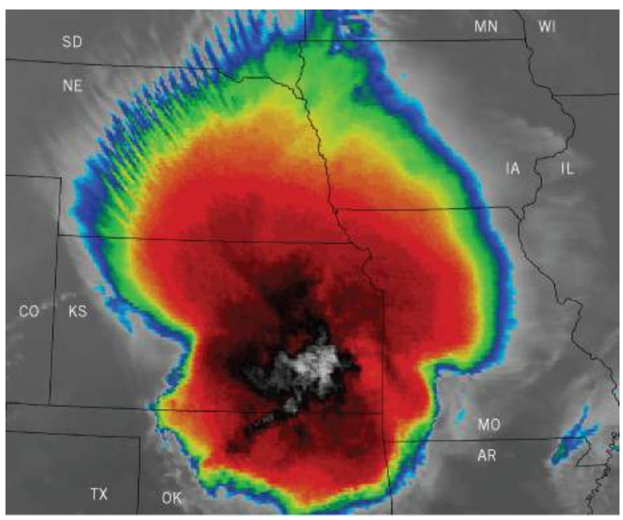
*Reported in the *Bulletin of the American Meteorological Society*, Vol. 88, No. 4 (April 2007): 490.

Mesoscale Convective Complexes

A **mesoscale convective complex (MCC)** consists of many individual thunderstorms organized into a large oval to circular cluster that can span the size of a state. Mesoscale convective complexes tend to form most frequently in the Great Plains. These usually slow-moving complexes may persist for more than 12 hours (Figure 10.11).

Figure 10.11 A powerful mesoscale convective complex

This large mesoscale convective complex was centered near the Missouri and Kansas border on June 5, 2014. This is a false color infrared image showing the cloud top of this convective complex. Dark red shows the highest, and thus the coldest, part of this structure. Although not visible, numerous overshooting cloud tops are present, indicating that the complex is composed of numerous cumulonimbus towers.



When conditions are favorable, an MCC can develop from a group of ordinary thunderstorms or behind a weakening squall line after sunset and continue into the early morning. One of these storm clusters may have awakened you at night with vivid lightning and rumbling thunder. The transformation of ordinary thunderstorms into an MCC requires a strong low-level flow of very warm and moist air. This flow enhances instability, which in turn spurs convection and cloud development. As long as favorable conditions prevail, MCCs remain self-propagating as gust fronts from existing cells lead to the formation of new powerful cells nearby. New thunderstorms tend to develop near the side of the complex that faces the incoming low-level flow of warm, moist air.

> Mesoscale convective complexes are large groups of thunderstorms that can be the size of a state.

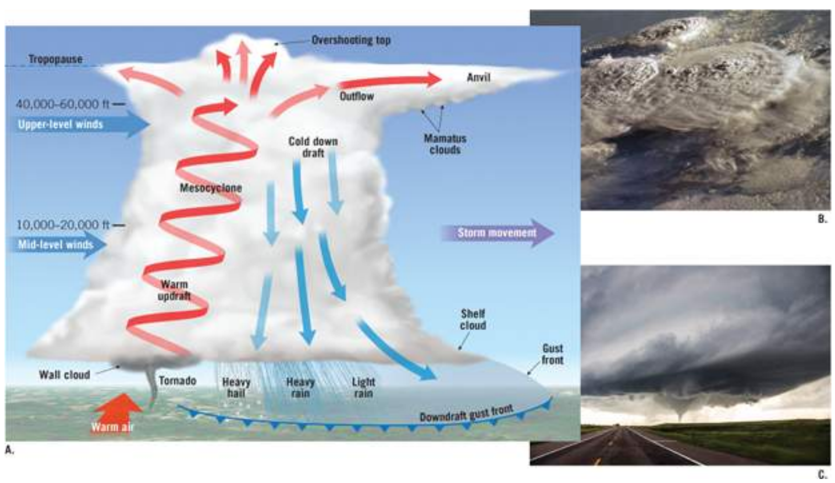
Although mesoscale convective complexes sometimes produce severe weather, they are also beneficial because they provide a significant portion of the growing-season rainfall to the agricultural regions of the central United States.

Supercell Thunderstorms

Some of our most dangerous weather is caused by a type of severe thunderstorm called a **supercell** (Figure 10.12). An estimated 2000 to 3000 supercell thunderstorms form annually in the United States. They represent just a small fraction of all thunderstorms, but they are responsible for a disproportionate share of the deaths, injuries, and property damage associated with severe weather. Fewer than half of all supercells produce tornadoes, yet virtually all of the strongest and most violent tornadoes are spawned by supercells.

Figure 10.12 Idealized supercell thunderstorm

A. This cross section shows the "anatomy" of a supercell. **B.** This photo of a cluster of supercell thunderstorms along the Manitoba–Minnesota border in September 1994 was taken from space by an astronaut. **C.** View from ground level of a towering supercell thunderstorm that has produced a tornado.



A supercell consists of a single, very powerful cell that may extend to a height of 20 kilometers (65,000 feet) or more. These massive cumulonimbus clouds have diameters ranging between about 20 and 50 kilometers (12 and 30 miles). Supercells tend to form along frontal boundaries separating warm and cold air masses and drylines, but they may also form in the warm sector of an mT air mass in a cyclonic system, near the center of low pressure.

> Supercell thunderstorms are strong isolated storms that tend to form along cold fronts or drylines.

Despite their single-cell structure, supercells are remarkably complex and can vary significantly from one structure to the next. The upper portion of a classic supercell thunderstorm takes the form of a large anvil that is blown downstream by strong upper-level winds—usually blowing from the west or northwest. Because they are characterized by strong updrafts, supercells exhibit overshooting tops. Supercells may also contain **mammatus clouds**, which are cloud pockets hanging downward from the underside of the cloud's anvil or, sometimes, from the base of the cloud (Figure 10.13).

Figure 10.13 **Mammatus sky**

The dark overcast of a mammatus sky, with its characteristic downward-bulging pouches, sometimes precedes a squall line. When a mammatus formation develops, it is usually after a cumulonimbus cloud reaches its maximum size and intensity. Its presence is generally a sign of an especially vigorous thunderstorm.

In addition to the availability of warm, moist air and instability, the formation of a supercell thunderstorm is aided by strong vertical wind shear, including both *speed shear* and *directional shear*. **Vertical speed shear** may exceed 40 knots (46 miles per hour) between the surface flow and midlevel winds—which means that if the surface winds are 10 knots (12 miles per hour), the winds at 6 kilometers (4 miles) above the ground will be about 50 knots (58 miles per hour). This significant increase in wind speed with height dramatically tilts the storm's updraft (Figure 10.12). This tilt causes the updraft and downdraft to be located in separate regions of the cloud, which reduces the chance of precipitation falling into the updraft and cutting off the cloud's moisture supply. Consequently, supercell thunderstorms are able to sustain themselves for 12 hours or more. Strong winds near the top of the cumulonimbus cloud carry the anvil away from the zone of upwelling. This mass transfer of air aloft promotes surface convergence that helps power the updraft.

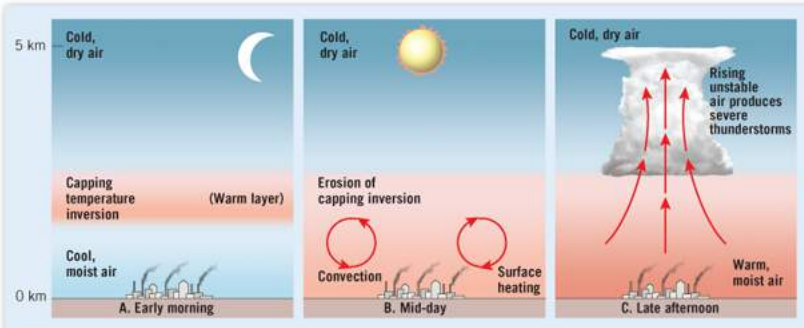
The presence of an intense rotating updraft is the main characteristic that sets supercell thunderstorms apart from ordinary thunderstorms. Strong **vertical directional shear**, which is the change in wind direction with height above the ground, contributes to the development of these rotational updrafts. In a typical supercell, the directional wind shift between the surface and the top of the cloud can be as much as 60 degrees or more. This change in wind direction helps rotate the updraft within the storm. It is within this column of cyclonically rotating air, called a **mesocyclone**, that tornadoes often form (see Figure 10.12). The rotation within a mesocyclone may be visible in the **wall cloud**—a dark, low-hanging cloud below the base of the supercell. Mesocyclones and wall clouds will be discussed in more detail later in the chapter in connection with tornado development.

Supercells tend to develop in the Great Plains and move toward the northeast. If you were in the path of a supercell, you would typically see a large anvil overhead and perhaps mammatus clouds and/or a shelf cloud. These ominous structures are followed by strong winds associated with the gust front. Next, light rain will start to fall, followed by heavier rain and perhaps small hail (see Figure 10.6). In very strong storms, the hail increases in size, and the precipitation and winds become incredibly loud as the storm moves overhead. Then, as the updraft region of the storm arrives, the hail and rain end—leaving an eerie quiet. Before this point you should seek shelter, because this is the region of the storm where tornadoes are potentially spawned.

The huge quantities of warm, moist air (latent heat) needed to sustain a supercell require special conditions. Studies suggest that the existence of a *capping inversion layer* a few kilometers above the surface helps provide this basic ingredient (Figure 10.14A). Recall that a temperature inversion, which is an increase in temperature with height, produces very stable atmospheric conditions that restrict vertical air movement. The presence of an inversion aids in the formation of very large thunderstorms by preventing large-scale convection of hot, moist air until late in the day, when temperatures are highest. With an inversion in place, surface heating continues to increase the temperature and moisture content of the layer of air trapped below the inversion (Figure 10.14B). Eventually, the air below the inversion becomes unstable enough to promote strong mixing, causing the inversion to erode. The buoyant air below "erupts" explosively at these sites, producing unusually large cumulonimbus towers (Figure 10.14C). It is from such clouds, with their concentrated, persistent rotating updrafts, that supercells form. Because the atmospheric conditions favoring the formation of severe thunderstorms often exist over a broad area, multiple supercells may develop simultaneously.

Figure 10.14 Capping temperature inversion

The formation of severe thunderstorms can be enhanced by the existence of a temperature inversion located a few kilometers above the surface.



Concept Checks 10.3

- How does a severe thunderstorm differ from an ordinary thunderstorm?
- How is a supercell different from an ordinary single-cell thunderstorm?
- Describe how the weather associated with a squall line is different from that of a supercell.
- What circumstances favor the development of mesoscale convective complexes?

10.4 Lightning and Thunder

LO 4 Explain what causes lightning and thunder.

Lightning is spectacular to watch, but it is also very dangerous. Globally, nearly 2000 lightning deaths occur each year, and approximately 100 of these take place in the United States (Table 10.1).

Table 10.1 Lightning Casualties in the United States, by Location or Activity

Rank	Location/Activity	Relative Frequency
1	Open areas (including sports fields)	45%
2	Going under trees to keep dry	23%
3	Water-related activities (swimming, boating, and fishing)	14%
4	Golfing (while in the open)	6%
5	Farm and construction vehicles (with open exposed cockpits)	5%
6	Corded telephone (number-one indoor source of lightning casualties)	4%
7	Golfing (while mistakenly seeking "shelter" under trees)	2%
8	Using radios and radio equipment	1%

Source: National Weather Service.

A storm is classified as a thunderstorm only after thunder is heard. Because thunder is produced by lightning, lightning must also be present (Figure 10.15). Lightning is similar to the electrical shock you may have experienced when touching a metal object on a very dry day. However, the intensity is dramatically different.

Figure 10.15 Summertime lightning display

A storm is classified as a thunderstorm only after thunder is heard. Because thunder is produced by lightning, lightning must also occur.

During the formation of a large cumulonimbus cloud, a separation of electric charge occurs; this means that part of the cloud develops an excess negative charge, whereas another part acquires an excess positive charge. What lightning does is equalize these electrical differences by producing a negative flow of current from the region of excess negative charge to the region with excess positive charge, or vice versa. Because air is a poor conductor of electricity (good insulator), the electrical potential (charge difference) must be very high before lightning will strike.

The most common type of lightning occurs between oppositely charged zones *within* a cloud or between clouds. About 80 percent of all lightning is of this type. It is called **sheet lightning** because it produces a bright but diffused illumination in parts of the cloud. The second type of lightning, in which the electrical discharge occurs between the cloud and Earth's surface, is often more dramatic. This **cloud-to-ground lightning** represents about 20 percent of lightning strokes and is the most damaging and dangerous form.

> Lightning within a cloud or between clouds is the most common, but cloud-to-ground lightning is the most dangerous.

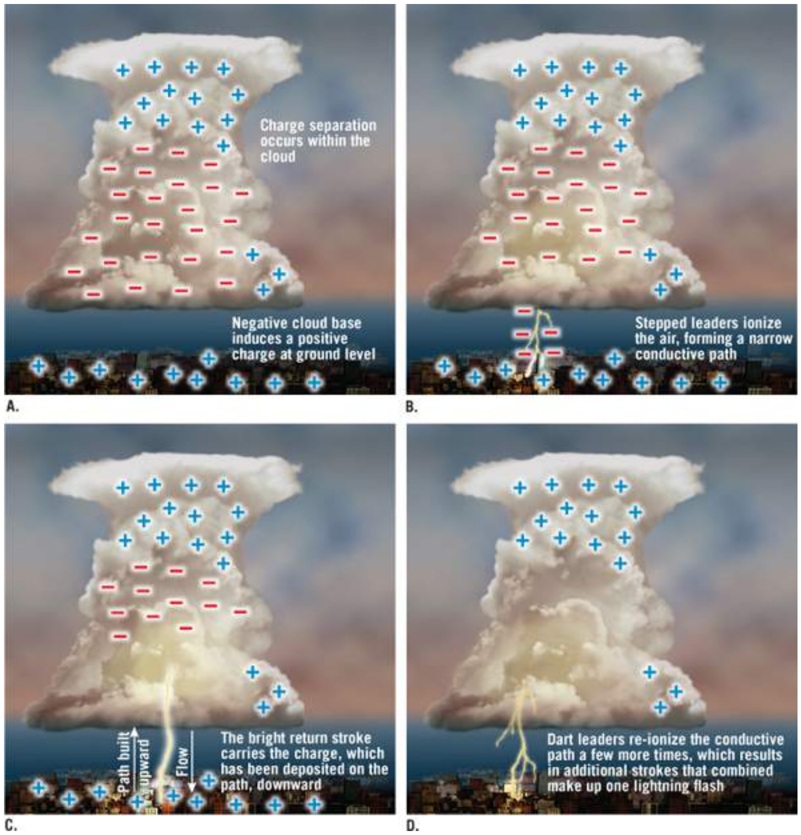
What Causes Lightning?

The origin of charge separation in clouds, although not fully understood, must hinge on rapid vertical movements within clouds because lightning occurs primarily in the violent mature stage of a cumulonimbus cloud. In the midlatitudes, the formation of these towering clouds is chiefly a spring and summertime phenomenon, which explains why lightning is seldom observed there in the winter. Furthermore, lightning rarely occurs before the growing cloud penetrates the 5-kilometer (16,000-foot) level, where sufficient cooling begins to generate ice crystals.

Cloud physicists have discovered that charge separation occurs when both ice crystals and raindrops exist in a thunderstorm. Experimentation shows that when ice particles and raindrops collide, ice crystals become positively charged and raindrops become negatively charged. The positively charged ice crystals are easily carried upward by the updraft, while the relatively heavy raindrops carry their negative charge toward the cloud base. As a result, the upper part of the cloud obtains a positive charge, while the lower portion of the cloud maintains an overall negative charge, with small positively charged pockets (Figure 10.16).

Figure 10.16 Discharge of a cloud via cloud-to-ground lightning

Examine this drawing carefully while reading the text.



> Lightning is caused by a difference in electrical charge within a cloud or between clouds, or between a cloud and the ground.

You might have wondered . . .

How frequently does lightning strike the ground in the United States?

Since 1989, the National Lightning Detection Network has recorded an average of about 25 million cloud-to-ground flashes per year in the contiguous 48 states. About half of all flashes have more than one ground-strike point, so more than 40 million points on the ground are struck in an average year.

As the cloud moves, the negatively charged cloud base alters the charge at the surface directly below by repelling negatively charged particles. Thus, the surface beneath the cloud acquires a net positive charge. These charge differences build to millions and even hundreds of millions of volts before a lightning stroke acts to discharge the negative region of the cloud by striking the positive area of the ground below or, more frequently, the positively charged areas within that cloud or a nearby cloud.

Lightning Strokes

High-speed cameras that take multiple images in close succession have greatly aided in the study of cloud-to-ground strikes (Figure 10.17). The images reveal the lightning that we see as a single flash is really several very rapid strokes between the cloud and the ground. We call the total discharge, which lasts only a few tenths of a second and appears as a bright streak, the **flash**. Individual components that make up each flash are termed **strokes**. Each stroke is separated by roughly 50 milliseconds, and there are usually three to four strokes per flash.* When a lightning flash appears to flicker, it is because your eyes discern the individual strokes that make-up the flash.

Figure 10.17 **Multiple lightning strokes of a single flash as recorded by a video camera**

Each stroke begins when the electrical field near the cloud base frees electrons in the air immediately below, thereby ionizing the air (Figure 10.16). Once ionized, the air becomes a conductive path with a radius of roughly 10 centimeters and a length of 50 meters. This path is called a **leader**. During this electrical breakdown, the mobile electrons in the cloud base begin to flow down this channel. This flow increases the electrical potential at the head of the leader, which causes the conductive path to extend even more through further ionization. Because this initial path extends itself toward Earth in short, nearly invisible bursts, it is called a **stepped leader**. Once this channel nears the ground, the positive electrical field at the surface produces a *streamer* that ionizes the remaining section of the path. With the path completed, the electrons begin to flow downward.

> During a lightning strike, the stepped leader forms a conductive path, allowing electrons to flow from the cloud to the ground.

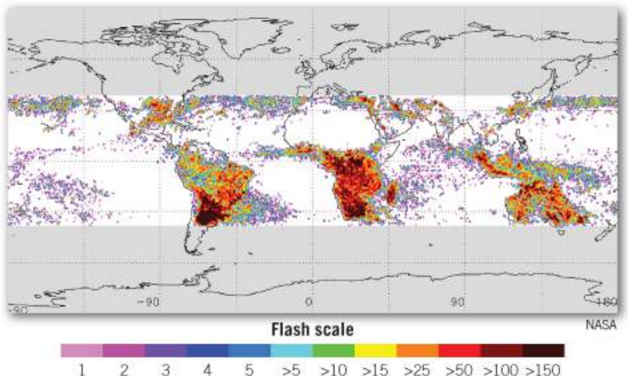
The initial flow of electrons begins near the ground. As the electrons at the lower end of the conductive path move toward Earth, electrons positioned successively higher up the channel begin to migrate downward. Because the path of electron flow is continually being extended upward, the accompanying electrical discharge is named the **return stroke**. As the wave front of the return stroke moves upward, the negative charge that was deposited on the channel is effectively lowered to the ground. This intense return stroke illuminates the conductive path and discharges the lowest kilometer or so of the cloud. During this phase, which is the most luminous part of a lightning flash, tens of coulombs of negative electrical charge are lowered to the ground.*

The first lightning stroke is usually followed by additional strokes that drain charges from higher areas within the cloud. Each subsequent stroke begins with a **dart leader** that follows the ionized channel produced by the stepped leader. The dart leader is continuous and less branched than the initial stepped leader. The total time of each lighting flash, which usually consists of three or four strokes, is less than one-quarter of a second.

Most lightning that strikes the ground consists of negatively charged particles (electrons) going from the cloud to the ground. Occasionally, however, the flow of current can consist of positively charged ions traveling from the cloud to the ground. This type of lightning tends to come from the anvil head of a towering cumulonimbus cloud, where positively charged particles accumulate. Although only 5 percent of lightning strikes are thought to be positively charged, this type of lightning is much more destructive. Positive lightning usually travels outside the cloud and strikes a negatively charged area at the surface that is often 10 kilometers (6 miles) or more from the cloud base, hence the expression "bolt from the blue."

Eye on the Atmosphere 10.1

This satellite image is a composite showing 3 months' worth of data from NASA's Lightning Imaging Sensor, which records all lightning strikes between 35° north and 35° south latitude.



Apply What You Know

1. What 3-month span does this image represent: June–August or December–February? How did you figure this out?
2. Why is there so much more lightning over land areas than over the oceans?

You might have wondered . . .

What are the chances of being struck by lightning?

Most people greatly underestimate the probability of being struck by lightning. According to the National Weather Service, the chance of an individual in the United States being killed or injured during a given year is 1 in 1,042,000. Assuming a life span of 80 years, a person's lifetime odds become 1 in 13,000.

Thunder

The electrical discharge of lightning superheats the air immediately around the lightning channel. In less than a second, the temperature rises by as much as 33,000°C. When air is heated this quickly, it expands fast enough to break the sound barrier and produces the sound we hear as **thunder**. Because lightning creates thunder, it is possible to estimate the distance to the stroke. Lightning is seen instantaneously, but the relatively slow sound waves, which travel approximately 330 meters (1000 feet) per second, reach us a little later. If thunder is heard 5 seconds after the lightning is seen, the lightning occurred about 1650 meters (approximately 1 mile) away.

> Thunder is the sound created when air expands as it is heated by a lightning stroke.

The thunder we hear as a rumble is produced along a long lightning path located at some distance from the observer. The sound that originates along the path nearest the observer arrives before the sound that originated farthest away. This factor lengthens the duration of the thunder. Reflection of the sound waves by mountains or tall buildings can further delay their arrival and adds to this effect. When lightning occurs more than 20 kilometers (12 miles) away, thunder is rarely heard. This type of lightning, popularly called *heat lightning*, is no different from the lightning we associate with thunder.

You might have wondered . . .

About how many people who are struck by lightning are actually killed?

According to the National Weather Service, about 10 percent of lightning strike victims are killed; 90 percent survive. However, survivors are not unaffected—many suffer severe, lifelong injuries and disabilities.

Concept Checks 10.4

- What is the difference between sheet lightning and cloud-to-ground lightning?
- How is thunder produced?
- What is heat lightning?

* One millisecond equals one one-thousandth (1/1000) of a second.

* A coulomb is a unit of electrical charge equal to the quantity of charge transferred in 1 second by a steady current of 1 ampere.

10.5 Tornadoes

LO 5 Describe the structure and basic characteristics of tornadoes.

Tornadoes are local storms of short duration that must be ranked high among nature's most destructive forces (Figure 10.18). Their sporadic occurrence and violent winds cause many deaths each year. The nearly total destruction in some stricken areas has led many to liken a tornado's passage to bombing raids during war.

Figure 10.18 Condensation and debris make tornadoes visible

A tornado is a violently rotating column of air in contact with the ground. The air column is visible when it contains condensation or when it contains dust and debris. Often the appearance is a result of both. When the column of air is aloft and does not produce damage, the visible portion is properly called a *funnel cloud*.

Such was the case during a very stormy period in late May 2013 in central Oklahoma. On May 20, an EF-5 tornado, the most severe category (see Table 10.3,), struck the city of Moore. Peak winds were estimated at 340 kilometers (210 miles) per hour. The storm claimed 25 lives and injured more than 350 people. Entire neighborhoods were destroyed; at least 13,000 structures were destroyed or damaged, with estimated costs exceeding $2 billion (Figure 10.19). The tornado was one of many that occurred across the Great Plains over a 2-day span, including five that struck central Oklahoma on May 19. This was not the first time Moore had experienced such a storm; 13 years earlier, in May 1999, an even stronger and deadlier tornado hit this community.

Figure 10.19 Tornado destruction at Moore, Oklahoma

On May 20, 2013, central Oklahoma was devastated by an EF-5 tornado, the most severe category. At its peak, the tornado was 2.1 kilometers (1.3 miles) wide and had winds of 340 kilometers (210 miles) per hour.

> A tornado is a violently rotating column of air.

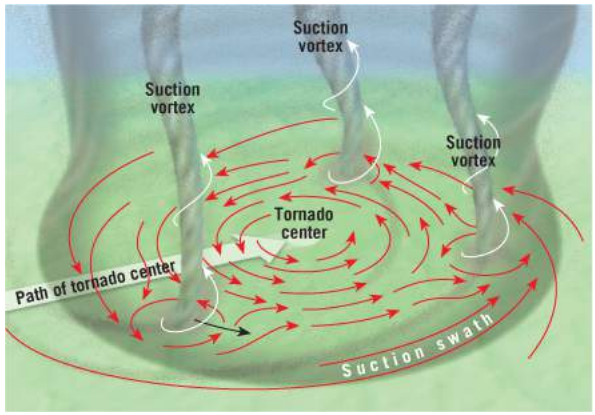
Tornadoes, sometimes called *twisters* or *cyclones*, are violent windstorms that take the form of a rotating column of air, or *vortex*, that extends downward from a cumulonimbus cloud. Pressures within some tornadoes have been estimated to be as much as 10 percent lower than immediately outside the storm. Drawn by the much lower pressure in the center of the vortex, air near the ground rushes into the tornado from all directions. As the air streams inward, it is spiraled upward around the core until it eventually merges with the airflow of the parent thunderstorm deep in the cumulonimbus tower.

Because of this rapid drop in pressure, air sucked into the storm expands and cools adiabatically. If the air cools below its dew point, the resulting condensation creates an ominous-appearing cloud that may darken as it moves across the ground, picking up debris. Occasionally, when the inward spiraling air is relatively dry, no condensation funnel forms. In such cases, the vortex is made visible only by the material that it vacuums from the surface and carries aloft.

A tornado may consist of a single vortex, but within many stronger tornadoes are smaller intense whirls called *suction vortices* that orbit the center of the larger tornado circulation (Figure 10.20). Suction vortices have diameters of only about 10 meters (30 feet) and usually form and die out in less than a minute. They can occur in all sorts of tornado sizes, from huge “wedges” to narrow “ropes.” Suction vortices are responsible for most of the narrow, short swaths of extreme damage that sometimes occur along tornado tracks. The tornadoes in this latter category are called **multiple-vortex tornadoes**. Meteorologists have since determined that most reports of several tornadoes occurring at once were in fact a single multiple-vortex tornado.

Figure 10.20 **Multiple-vortex tornado**

Some tornadoes have multiple suction vortices. These small and very intense vortices are roughly 10 meters (30 feet) across and move in a counterclockwise path around the tornado center. Because of this multiple-vortex structure, one building might be heavily damaged whereas another one, just 10 meters away, might suffer little damage.



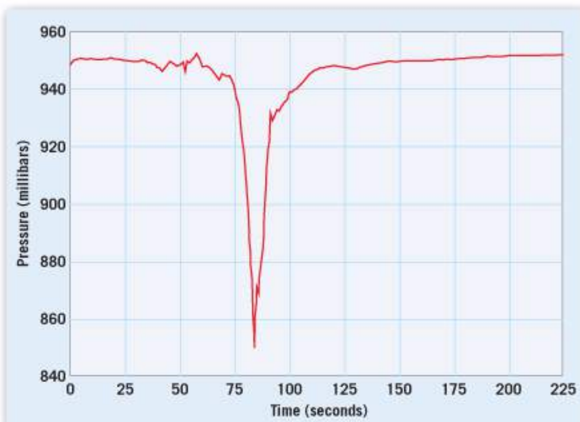
Because of the tremendous pressure gradient associated with a strong tornado, maximum winds can sometimes exceed 480 kilometers (300 miles) per hour. Reliable wind-speed measurements using traditional anemometers are lacking, but using Doppler radar observations, scientists measured wind speeds of 486 kilometers (302 miles) per hour in a devastating tornado that struck the Oklahoma City area in May 1999.

Most records of changes in atmospheric pressure associated with the passage of a tornado are estimates based on a few storms that happened to pass a nearby weather station or were studied by storm-chasing meteorologists with mobile equipment. Many attempts have been made to deploy instruments in the path of a tornado, but only a few have met with success. One successful measurement occurred in Manchester, South Dakota, on June 24, 2003. Meteorologists chasing a supercell thunderstorm deployed a specially designed probe in the path of a violent tornado. The tornado passed directly over the instrument package, which measured a sharp drop of 100 millibars over a span of about 40 seconds

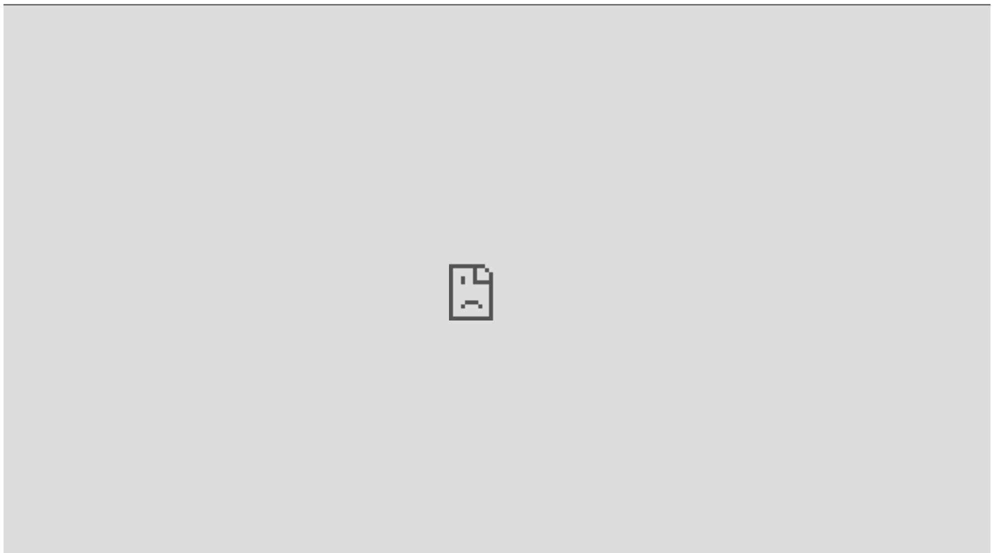
(Figure 10.21). Gathering such data is challenging because tornadoes are short-lived, highly localized, and dangerous. The development of Doppler radar, however, has improved our ability to study tornado-producing thunderstorms. As you will see later in the chapter, this technology is allowing meteorologists to expand our understanding from a safe distance.

Figure 10.21 Pressure change with the passage of a tornado

This graph shows the dramatic pressure change of 100 millibars in just 40 seconds that occurred as a violent tornado passed directly over a specially designed probe that had been placed in the storm's path just moments earlier. Manchester, South Dakota, June 24, 2003.



Watch **Video: NSSL in the Field**



Concept Checks 10.5

- Why do tornadoes have such high wind speeds?
- What makes the rotating air column of a tornado visible?
- Explain multiple-vortex tornadoes.

10.6 Development and Occurrence of Tornadoes

LO 6 Summarize the atmospheric conditions and locations that are favorable to the formation of tornadoes.

Tornadoes form in association with severe thunderstorms that produce high winds, heavy (sometimes torrential) rainfall, and often damaging hail. Although hail may or may not precede a tornado, the area of a thunderstorm where the strongest tornadoes occur is usually found to the rear of the hail-producing portion of the storm. Fortunately, fewer than 1 percent of all thunderstorms produce tornadoes.

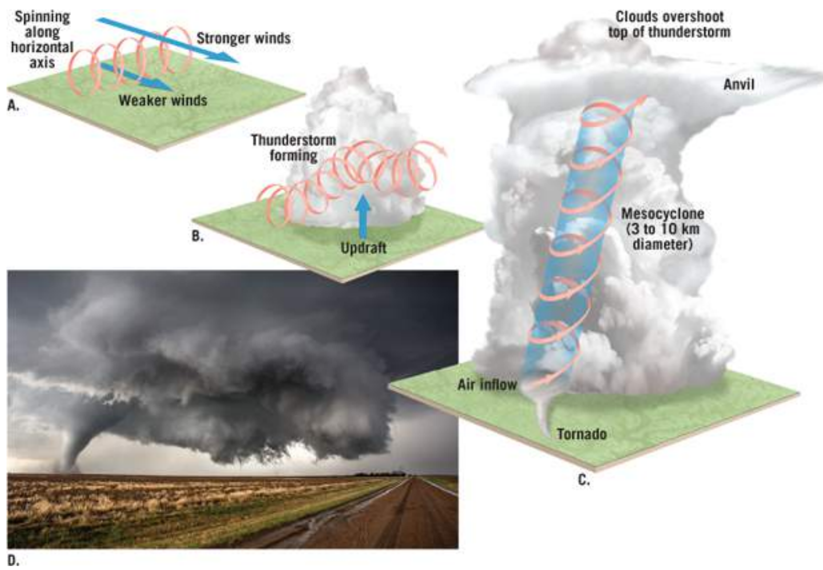
Tornado Development

Tornadoes can form in any situation that produces severe weather, although the most intense tornadoes usually form in association with supercells. An important precondition linked to tornado formation is the development of a mesocyclone. Recall that a *mesocyclone* is a vertical cylinder of rotating air, typically about 3 to 10 kilometers (2 to 6 miles) across, that develops in the updraft of a severe thunderstorm. The formation of this large vortex often precedes tornado formation by 30 minutes or so.

Mesocyclone formation depends on the presence of vertical wind shear. Moving upward from the surface, winds change direction from southerly to westerly, and the wind speed increases. The speed wind shear—stronger winds aloft and weaker winds near the surface—produces a rolling motion about a horizontal axis, as shown in Figure 10.22A. If conditions are right, strong updrafts in the storm tilt the horizontally rotating air to a nearly vertical alignment (see Figure 10.22B). This produces the initial rotation within the cloud interior.

Smartfigure 10.22 The formation of a mesocyclone often precedes tornado formation

A. Winds are stronger aloft than at the surface (called *speed wind shear*), producing a rolling motion about a horizontal axis. **B.** Strong thunderstorm updrafts tilt the horizontally rotating air to a nearly vertical alignment. **C.** The mesocyclone, a vertical cylinder of rotating air, is established. **D.** If a tornado develops, it will descend from a slowly rotating wall cloud in the lower portion of the mesocyclone.



Watch SmartFigure: Mesocyclones and Tornadoes

At first, the mesocyclone is wide, short, and rotates relatively slowly. Subsequently, the mesocyclone is stretched vertically and narrowed horizontally, causing wind speeds to accelerate in an inward vortex—just as spinning ice skaters spin faster by pulling their arms toward their bodies. Next, the narrowing column of rotating air stretches downward until a portion of the cloud protrudes below the cloud base to produce a very dark, slowly rotating *wall cloud*. Finally, a slender and rapidly spinning vortex may emerge from the edge of the wall cloud to form a *funnel cloud*. If the rotation makes contact with Earth's surface, it is classified as a *tornado*.

> A tornado usually descends from the edge of a wall cloud below the mesocyclone.

The formation of a mesocyclone does not necessarily mean that tornado formation will follow. Only about half of all mesocyclones produce tornadoes. The reason for this is not yet understood; therefore, forecasters cannot determine in advance which mesocyclones will spawn tornadoes.

Tornado Occurrence

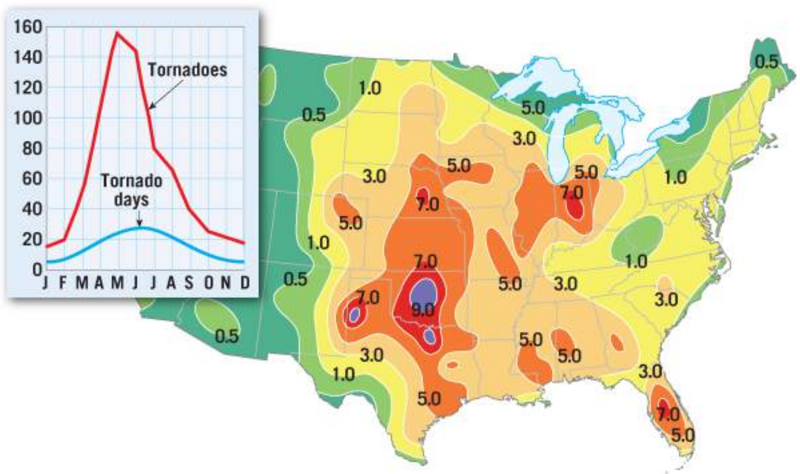
Recall that severe thunderstorms—and hence, tornadoes—are most often spawned along a cold front or dryline of a midlatitude cyclone that has produced a supercell thunderstorm. Throughout the spring, air masses associated with midlatitude cyclones are most likely to have greatly contrasting conditions. Continental polar (cP) air from Canada is still very cold and dry, whereas maritime tropical (mT) air from the Gulf of Mexico is warm, humid, and unstable. The greater the contrast, the more intense the storm tends to be.

> The peak season for tornadoes occurs in the spring.

These two contrasting air masses are most likely to meet in the central United States because there is no significant natural barrier separating polar air moving toward the equator and moist tropical air moving northward out of the Gulf of Mexico. Consequently, this region generates more tornadoes than any other part of the country or, in fact, the world. On average, nearly 1300 tornadoes are reported annually in the United States. However, the actual number that occur from one year to the next varies greatly. From 2000 through 2016, for example, yearly totals ranged from a low of 935 in 2002 to a high of 1817 in 2004. Figure 10.23 depicts the average annual tornado incidence in the United States (per 10,000 square miles) over a 27-year period.

Figure 10.23 **Tornado occurrence**

The map shows average annual tornado incidence per 26,000 square kilometers (10,000 square miles) for a 27-year period. The graph shows average number of tornadoes and tornado days each month in the United States for the same period.



Tornadoes can occur during every month of the year. April through June is the period of greatest tornado frequency in the United States, and December and January are the months of lowest activity. More than 40 percent of all tornadoes take place during the spring. Fall and winter, by contrast, together account for only 19 percent (Figure 10.23). In late February, when the incidence of tornadoes begins to increase, the center of maximum frequency lies over the central Gulf states. During March, this center moves eastward, to the southeastern Atlantic states, with tornado frequency reaching its peak in April.

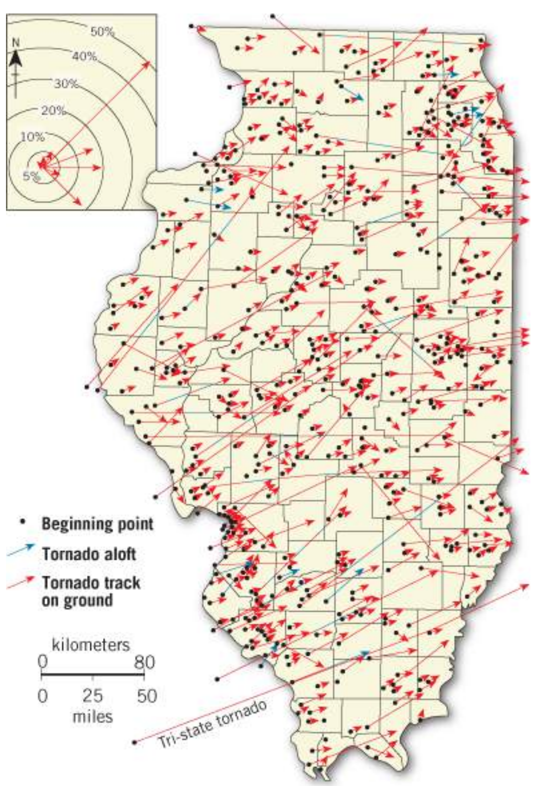
During May and June, the center of maximum frequency moves northward into the Great Plains and then to the Northern Plains and Great Lakes area. This drift is due to the northward penetration of warm, moist air while contrasting cool, dry air still surges in from the north and northwest. Fall and winter cooling results in fewer and fewer encounters between warm and cold air masses, and tornado frequency returns to its lowest level by December.

Profile of a Tornado

The average tornado has a diameter between 150 and 600 meters (500 to 2000 feet), travels across the landscape at approximately 45 kilometers (30 miles) per hour, and cuts a path about 26 kilometers (16 miles) long. Because many tornadoes occur slightly ahead of a cold front, in the zone of southwest winds, most move toward the northeast. The Illinois example shown in Figure 10.24 demonstrates this fact well. The figure also shows that many tornadoes do not fit the description of the "average" tornado.

Figure 10.24 Paths of Illinois tornadoes

Because most tornadoes occur slightly ahead of a cold front, in the zone of southwest winds, they tend to move toward the northeast. Tornadoes in Illinois verify this. More than 80 percent of the tornadoes in this diagram exhibited directions of movement toward the northeast through east.



Of the hundreds of tornadoes reported in the United States each year, more than half are comparatively weak and short-lived. Most of these small tornadoes have lifetimes of 3 minutes or less and paths that seldom exceed 1 kilometer (0.6 mile) in length and 100 meters (330 feet) in width. Typical wind speeds are on the order of 150 kilometers (90 miles) per hour or less. On the other end of the tornado spectrum are the infrequent and often long-lived violent tornadoes (Table 10.2). Although large tornadoes constitute only a small percentage of the total reported, their effects are often devastating. Such tornadoes may exist for periods exceeding 3 hours and produce an essentially continuous path of destruction more than 150 kilometers (90 miles) long and perhaps 1 kilometer (0.6 mile), or more in width. Maximum winds range beyond 480 kilometers (300 miles) per hour (Figure 10.25).

Table 10.2 Tornado Extremes

Tornado Characteristic	Value	Date	Location
World's deadliest single tornado	1300 dead, 12,000 injured	April 26, 1989	Salturia and Manikganj, Bangladesh
U.S. deadliest single tornado	695 dead	March 18, 1925	Missouri–Illinois–Indiana
U.S. deadliest tornado outbreak	747 dead	March 18, 1925	Missouri–Illinois–Indiana (includes the Tri-State Tornado deaths)
Biggest 24-hour total tornado outbreak	190 tornadoes	April 27, 2011	Eastern third of the United States
Calendar month with greatest number of tornadoes	753 tornadoes	April 2011	United States
Widest tornado (diameter*)	4184 m (2.6 miles) in width	May 31, 2013	El Reno, Oklahoma; EF-5 tornado
Highest recorded tornadic wind speed†	135 m/s (302 mph)	May 8, 1999	Bridge Creek, Oklahoma
Highest elevation tornado	3650 m (12,000 ft)	July 7, 2004	Sequoia National Park, California
Longest tornado transport	A personal check carried 359 km (223 miles)	April 11, 1991	Stockton, Kansas, to Winnetoon, Nebraska

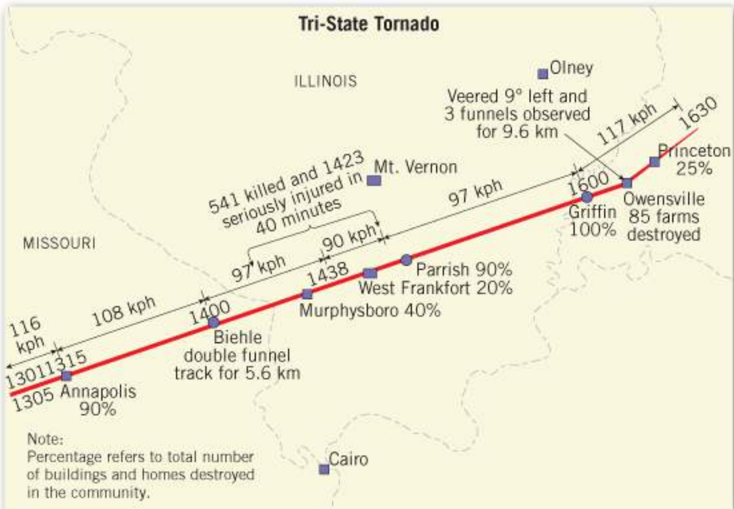
Source: National Weather Service, Storm Prediction Center.

*The National Weather Service now defines "widest" as the maximum width of tornado damage.

†By necessity, this value is restricted to the small number of tornadoes sampled by Doppler radar.

Figure 10.25 **Tri-State Tornado**

The deadliest U.S. tornado on record occurred on March 18, 1925. The tornado remained on the ground for more than 350 kilometers (219 miles), killing 745 and injuring 2027 people. The numbers immediately above the track line are a reference to time of day (24-hour clock).



Watch **Video: The Deadliest Tornado Since Modern Recordkeeping Began**

You might have wondered . . .

What is "Tornado Alley"?

Tornado Alley is a nickname the popular media and others use to refer to the broad swath of high tornado occurrence in the central United States (see Figure 10.23). The heart of Tornado Alley stretches from the Texas panhandle through Oklahoma and Kansas to Nebraska. It's important to remember that violent (killer) tornadoes occur outside Tornado Alley every year. Tornadoes can occur almost anywhere in the United States.

Concept Checks 10.6

- When is "tornado season"? Why does it occur at this time of year?
- Why does the area of greatest tornado frequency migrate?
- In what direction do most tornadoes move? Explain.

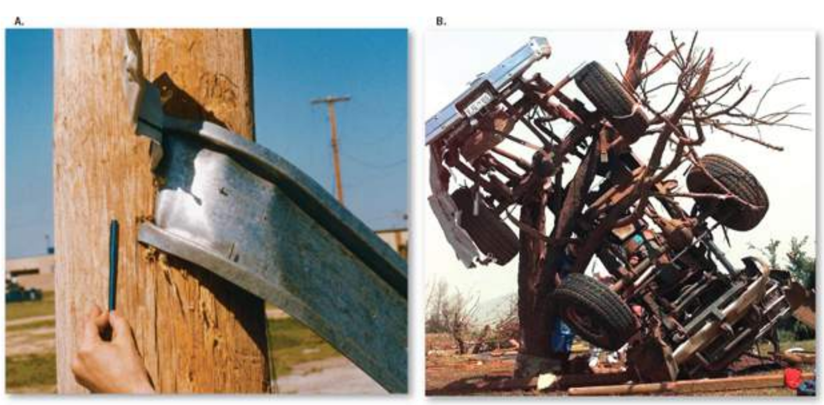
10.7 Tornado Destruction and Tornado Forecasting

LO 7 Describe tornado intensity. Distinguish between a tornado watch and a tornado warning, and discuss the role of Doppler radar in the warning process.

Because tornadoes generate the strongest winds in nature, they have accomplished many seemingly impossible tasks, such as driving a piece of straw through a thick wooden plank and uprooting huge trees (Figure 10.26). Although it may seem impossible for winds to cause some of the damage attributed to tornadoes, tests in engineering facilities have repeatedly demonstrated that winds in excess of 320 kilometers (200 miles) per hour are capable of incredible feats.

Figure 10.26 The force of tornado winds

A. The force of the wind during a tornado near Wichita, Kansas, in April 1991 was enough to drive this piece of metal into a utility pole. **B.** The remains of a truck wrapped around a tree in Bridge Creek, Oklahoma, on May 4, 1999, following a major tornado outbreak.



There is a long list of documented examples. In 1931, a tornado actually carried an 83-ton railroad coach and its 117 passengers 24 meters (80 feet) through the air and dropped them in a ditch. A year later, near Sioux Falls, South Dakota, a steel beam 15 centimeters (6 inches) thick and 4 meters (13 feet) long was ripped from a bridge, flew more than 300 meters (nearly 1000 feet), and perforated a hardwood tree 35 centimeters (14-inches) thick. In 1970, an 18-ton steel tank was carried nearly 1 kilometer (0.6 mile) at Lubbock, Texas. Fortunately, the winds associated with most tornadoes are not this strong.

Tornado Intensity

Most tornado losses are associated with a few storms that strike urban areas or devastate entire small communities. The destruction wrought by such storms depends to a significant degree on the strength of the winds. The commonly used guide to tornado intensity is the **Enhanced Fujita Scale**, or the **EF Scale** for short (Table 10.3). Because tornado winds cannot be measured directly, a rating on the EF Scale is determined by assessing the damage produced by a storm. Although widely used, the EF Scale is not perfect. For example, tornadoes that occur over a farm field cause little damage, no matter how strong the tornado might be.

Table 10.3 Enhanced Fujita Scale*

Scale	Wind Speed km/hr	Wind Speed mi/hr	Damage
EF-0	105–137	65–85	*Light.* Some damage to siding and shingles.
EF-1	138–177	86–110	*Moderate.* Considerable roof damage. Winds can uproot trees and overturn single-wide mobile homes. Flagpoles bend.
EF-2	178–217	111–135	*Considerable.* Most single-wide mobile homes destroyed. Permanent homes can shift off foundations. Flagpoles collapse. Softwood trees debarked.
EF-3	218–265	136–165	*Severe.* Hardwood trees debarked. All but small portions of houses destroyed.
EF-4	266–322	166–200	*Devastating.* Complete destruction of well-built residences and large sections of school buildings.
EF-5	>322	>200	*Incredible.* Significant structural deformation of mid- and high-rise buildings.

*The original Fujita scale was developed by T. Theodore Fujita in 1971 and put into use in 1973. The Enhanced Fujita Scale is a revision that was adopted in February 2007.

> The Enhanced Fujita Scale rates tornadoes based on the extent of damage they cause.

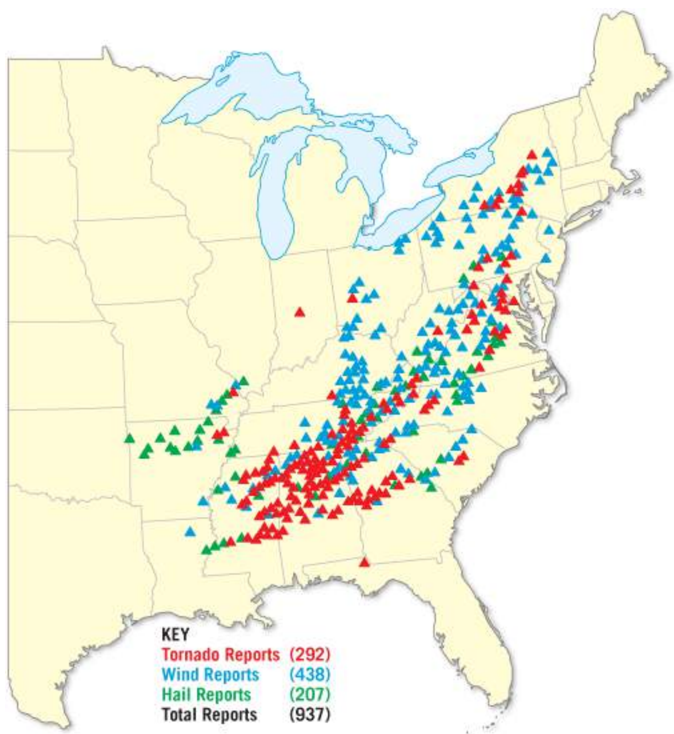
The drop in atmospheric pressure associated with the passage of a tornado plays a *minor role* in producing tornado damage. Most structures have sufficient venting to allow for the sudden drop in pressure. Opening windows, once thought to be a way to minimize damage by allowing inside and outside atmospheric pressure to equalize, is no longer recommended. In fact, if a tornado gets close enough to a structure for a significant pressure drop to occur, strong winds probably will have already caused significant damage.

Loss of Life

Most tornado injuries and deaths result from flying debris. For the United States, the average annual death toll from tornadoes is about 60 people. However, the actual number of deaths each year can depart significantly from the average. During the April 25–28, 2011, tornado outbreak, for example, 362 tornadoes brought death and destruction to a 16-state region east of the Mississippi River. More than 300 people died, and nearly 2200 people were injured (Figure 10.27).

Figure 10.27 Major tornado outbreak

On April 25–28, 2011, 292 tornado reports were issued over much of the southwestern United States. It was the largest, costliest, and one of the deadliest tornado outbreaks ever recorded since the Tri-State Tornado of 1925. High winds and hail also contributed to the destruction.

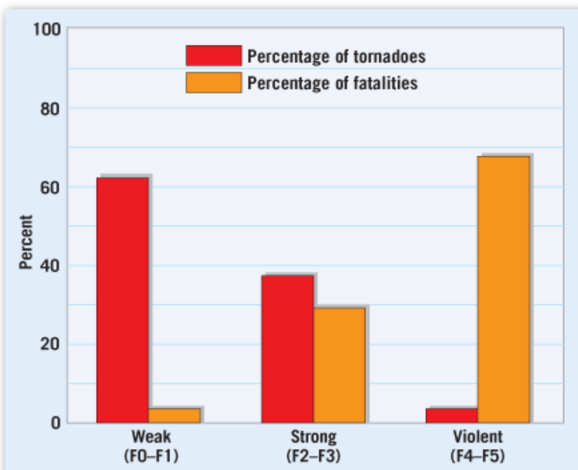


The proportion of tornadoes that result in loss of life is small. In most years, slightly less than 2 percent of all reported tornadoes in the United

States are “killer tornadoes.” Although the percentage of tornadoes that result in death is small, every tornado is potentially lethal. Figure 10.28, which compares tornado fatalities with storm intensities, illustrates that the majority (63 percent) of tornadoes are weak, and tornadoes of greater intensity tend to be fewer in number. The distribution of tornado fatalities, however, is just the opposite. Although only 2 percent of tornadoes are classified as violent, they account for nearly 70 percent of the deaths.

Figure 10.28 **Tornado intensity and fatalities**

The bar graph compares the percentage of tornadoes in each intensity category with the percentage of fatalities associated with that category. Because this study was completed prior to the adoption of the EF Scale, storm intensities are expressed using the F Scale. Wind speeds (mph) for this scale are F-0 (<72), F-1 (72–112), F-2 (113–157), F-3 (158–206), F-4 (207–260), F-5 (>260).



> Tornado fatalities have decreased greatly due to improved technology and warning systems, as well as a better understanding of tornadoes.

Tornado Forecasting

Because tornadoes are localized, short-lived phenomena, they are among the most difficult weather features to precisely forecast. Nevertheless, the prediction, detection, and monitoring of such storms are among the most important services provided by professional meteorologists. The timely issuance and dissemination of watches and warnings are critical to the protection of life and property (see Severe & Hazardous Weather 10.3).

Severe & Hazardous Weather 10.3

Surviving a Violent Tornado

On July 13, 2004, much of northern and central Illinois was put on tornado watch. A large supercell had developed in the northwestern part of the state and was moving southeast. The National Weather Service issued a *severe thunderstorm warning* at 2:29 p.m. Minutes afterward, a tornado developed. Twenty-three minutes later, the quarter-mile-wide twister had carved a 9.6-mile-long path across the rural Illinois countryside.

What, if anything, made this storm special or unique? For one, this tornado attained EF-4 status; fewer than 1 percent of tornadoes reach this level of severity. But what was most remarkable is that no one was killed or injured when the Parsons Manufacturing facility, west of the small town of Roanoke, took a direct hit while the storm was most intense. At the time, 150 people were in the 250,000-square-foot facility when it was flattened—cars were twisted into gnarled masses, and debris was strewn for miles (Figure 10.D).

Figure 10.D Aftermath of a violent central Illinois tornado

The quarter-mile-wide tornado had wind speeds reaching 240 miles per hour. Despite total destruction of the Parsons Manufacturing plant, 150 people emerged without injury.

How did 150 people escape death or injury?

How did 150 people escape death or injury? Foresight and planning saved them. More than 30 years earlier, company owner Bob Parsons was inside his first factory when a small tornado passed close enough to blow out windows. Later, when a new facility was being built, specifications for the plant included restrooms that doubled as tornado shelters, with steel-reinforced concrete walls and 8-inch-thick concrete ceilings. In addition, the company developed a severe weather plan. When the 2004 severe thunderstorm warning was issued, the emergency response team leader at the Parsons plant was immediately notified. A few moments later, he went outside and observed a rotating wall cloud with a developing funnel cloud. He radioed back to the office to institute the company's severe weather plan, and employees were directed to their designated storm shelters. Fortunately, because the plant had been conducting semiannual tornado drills, all 150 people reached shelters in less than 4 minutes. The emergency response team leader was the last person to reach a shelter, less than 2 minutes before the tornado destroyed the plant. The total number of U.S. tornado deaths in 2004 was 36—a toll that might have been much higher. The building of tornado shelters and the development of an effective severe storm plan made the difference between life and death for 150 people at Parsons Manufacturing.

Weather Safety

When a tornado watch is issued, you should keep abreast of local weather reports and stay alert for a tornado warning. The National Weather Service recommends the following in the event of a tornado warning.

- *In a building*: Go to the innermost room on the lowest floor of a home or sturdy building.
- *In your car*: If the tornado is very far away, drive out of the area and seek shelter! Otherwise, leave your car and lie face down, flat in a ditch.
- *Outdoors*: Seek shelter! Otherwise, lie face down, flat in a ditch far away from cars and trees.

Apply What You Know

1. List two factors that allowed employees of Parsons Manufacturing to avoid injury or death from the 2004 tornado.
2. What safety precautions should you take during a tornado watch? Tornado warning?

The mission of the National Weather Service's Storm Prediction Center (SPC) located in Norman, Oklahoma, is to provide timely and accurate forecasts and watches for severe thunderstorms and tornadoes. *Severe convective outlooks* are issued several times daily. *Day 1* outlooks identify areas likely to be affected by severe thunderstorms during the next 24 hours, and *day 2* outlooks extend the forecast through the following day. Both outlooks describe the type, coverage, and likelihood of the severe weather expected. Many local NWS field offices also issue severe weather outlooks that provide a more focused local description of the severe weather potential for the next 12 to 24 hours. Forecasting tools are discussed in more detail in Chapter 12.

Tornado Watches and Warnings

Tornado watches alert the public to the possibility of tornadoes over a specified area for a particular time interval. Watches serve to fine-tune forecast areas already identified in severe weather outlooks. A typical watch covers an area of about 65,000 square kilometers (25,000 square miles) for a 4- to 6-hour period. Watches are generally reserved for organized severe weather events where the tornado threat will affect at large area and/or persist for at least 3 hours. Watches typically are not issued when the threat is thought to be isolated and/or short-lived.

> A tornado watch is issued when conditions are favorable for the development of a tornado.

A **tornado warning**, by contrast, is issued by local offices of the National Weather Service when a tornado has been actually sighted in an area or is indicated by weather radar. It warns of a high probability of imminent danger. Warnings are issued for much smaller areas than watches, usually covering portions of a county or counties. In addition, they are in effect for much shorter periods, typically 30 to 60 minutes. Because a tornado warning may be based on an actual sighting, warnings are occasionally issued after a tornado has already developed. However, most warnings are issued before a tornado forms, sometimes by several tens of minutes, based on Doppler radar data and/or spotter reports of funnel clouds or cloud-base rotation.

> A tornado warning is issued if a tornado has been spotted or is indicated by radar.

Eye on the Atmosphere 10.2

This satellite image shows a portion of the diagonal path left by a tornado as it moved across northern Wisconsin in 2007.

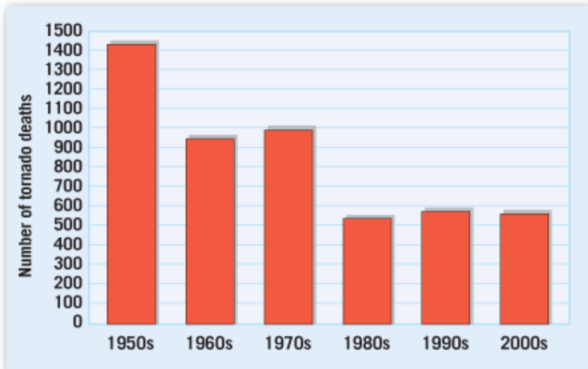
Apply What You Know

1. Toward what direction did the storm advance: the northeast or the southwest?
2. Is it more probable that the storm took place in March or June? Why is the month you selected more likely?

If the direction and the approximate speed of the storm are known, an estimate of its most probable path can be made. Because tornadoes often move erratically, the warning area is fan shaped downwind from the point where the tornado has been spotted. Improved forecasts and advances in technology have contributed to a significant decline in tornado deaths over the past 50 years, a trend illustrated by Figure 10.29. During a span when the U.S. population grew rapidly, tornado deaths trended downward.

Figure 10.29 Number of tornado deaths in the United States by decade, 1950–2009

Even though the population has risen sharply since 1950, there has been a general downward trend in tornado deaths.



As noted earlier, the probability of one place being struck by a tornado, even in the area of greatest frequency, is slight. Nevertheless, tornadoes have provided many mathematical exceptions. For example, the small town of Codell, Kansas, was hit 3 years in a row—1916, 1917, and 1918—and each year on the same date, May 20! Needless to say, tornado watches and warnings should never be taken lightly.

Doppler Radar

The installation of **Doppler radar** across the United States in the late 1980s significantly improved our ability to track thunderstorms and issue warnings based on their potential to produce tornadoes (Figure 10.30). Doppler radar works by transmitting short pulses of electromagnetic energy, and a small fraction of the waves released are scattered by a storm and returned to the radar, creating an “echo.” The strength of the returning signal indicates rainfall intensity, and the time difference between the transmission and return of the signal indicates the distance to the storm.

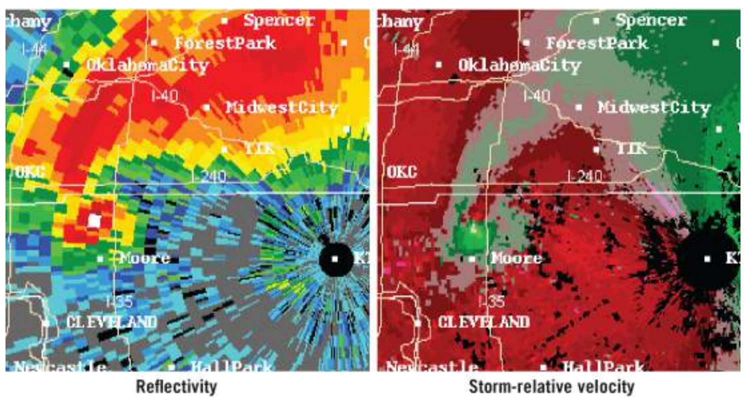
Figure 10.30 Doppler radar

A. Doppler radar sites in the United States. If you go to http://radar.weather.gov, you will see a similar map. You can click on any site to see the current National Weather Service Doppler radar display. **B.** Doppler on Wheels is a portable unit that researchers use in field studies of severe weather events.

Doppler radar can also detect motion within the storm (Figure 10.31). The principle involved is known as the *Doppler effect* (Figure 10.32). Air movement in clouds is determined by comparing the frequency of the reflected signal to that of the original pulse. The movement of precipitation toward the radar increases the frequency of reflected pulses, whereas motion away from the radar decreases the frequency. These frequency changes are then interpreted in terms of speed toward or away from the Doppler unit. This same principle allows police radar to determine the speed of moving cars. Unfortunately, a single Doppler radar unit cannot detect air movements that occur perpendicular to the radar beam. Therefore, when a more complete picture of the winds within a cloud mass is desired, two or more Doppler units must be used.

Figure 10.31 **Doppler radar images**

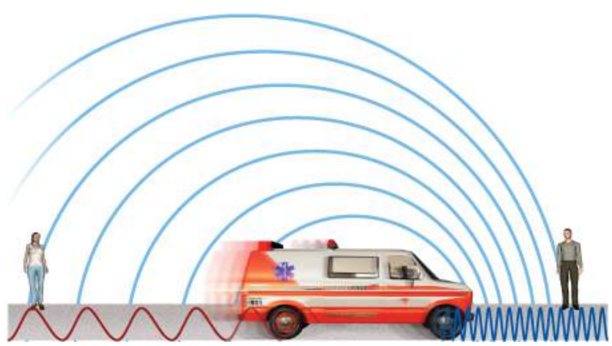
This is a dual Doppler radar image of an EF-5 tornado near Moore, Oklahoma, on May 3, 1999. The left image (reflectivity) shows precipitation in the supercell thunderstorm. The right image shows motion of the precipitation along the radar beam—that is, how fast rain or hail is moving toward or away from the radar. In this example, the radar was unusually close to the tornado—close enough to make out the signature of this tornado in the hooked-shaped echo visible in the lower left quadrant.



Watch **Video: Identifying Tornadic Thunderstorms Using Radar Reflectivity Data**

Figure 10.32 Doppler effect

This everyday example of the Doppler effect illustrates the apparent lengthening and shortening of wavelengths caused by the relative movement between a source and an observer.



> Doppler radar can be used to determine a storm's intensity and movement, as well as air movement within it.

Doppler radar can detect the initial formation and subsequent development of the mesocyclone within a severe thunderstorm that frequently precedes tornado development. Almost all (96 percent) mesocyclones produce damaging hail, severe winds, or tornadoes. Those that produce tornadoes (about 50 percent) can sometimes be distinguished by their strong wind speeds. Mesocyclones can sometimes be identified within parent storms 30 minutes or more before tornado formation and, if a storm is large, at distances up to 230 kilometers (140 miles). Ever since the implementation of the national Doppler network, the average lead time for tornado warnings has increased from less than 5 minutes in the late 1980s to about 13 minutes today.

Doppler radar technology has evolved due to the work of atmospheric scientists who developed **dual-polarization, or dual-pol, technology**, which provides forecasters with more precise information about the type of precipitation and its intensity, size, and location.

Dual-pol technology is now employed at every National Weather Service Doppler radar facility in the United States. The upgrade involved a hardware attachment to the radar dish that sends and receives both horizontal and vertical pulses of energy, providing a much more informative picture of what is happening in the atmosphere. It helps forecasters clearly identify and distinguish among rain, hail, snow or ice pellets, and other flying objects. Another important benefit is that dual-pol more clearly detects airborne debris. This allows forecasters to confirm that a tornado is on the ground and causing damage so they can more confidently warn communities in its path. This is especially helpful at night, when ground spotters are unable to see the tornado.

> Dual-polarization radar can be used to determine the types of particles in the storm and can confirm whether a tornado is on the ground causing damage.

You might have wondered . . .

How dangerous is it to be in a mobile home during a tornado?

Mobile homes represent a relatively small fraction of all residences in the United States. Yet, according to the National Weather Service, during the span 2000–2010, 52 percent of all tornado fatalities (314 of 604) occurred in mobile homes.

Concept Checks 10.7

■ Name the scale commonly used to rate tornado intensity. How is a rating on this scale determined?

■ Distinguish between a tornado watch and a tornado warning.

■ What advantages does Doppler radar have over conventional radar?

Concepts in Review

10.1 Thunderstorms

LO 1 List the three basic requirements for the formation of an ordinary thunderstorm, and describe the additional component required for a thunderstorm to become severe.

Key Terms

thunderstorm

- Thunderstorms form when warm, humid air is lifted into an unstable environment. Lifting mechanisms include surface heating, orographic lifting, surface convergence, and frontal lifting.
- The presence of wind shear is required for a thunderstorm to become severe.
- Thunderstorms occur year-round in many tropical areas, and during the warm months in the middle latitudes.

10.2 Ordinary Cell Thunderstorms

LO 2 Sketch and label simple diagrams that illustrate the three stages of an ordinary thunderstorm.

Key Terms

ordinary cell thunderstorms (ordinary thunderstorm, air-mass thunderstorm)

cumulus stage

entrainment

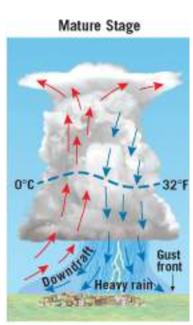
mature stage

microburst

dissipating stage

multicell thunderstorm

- Ordinary thunderstorms frequently occur in maritime tropical (mT) air during the spring and summer.
- The three stages in the development of these storms are: the cumulus stage, mature stage, and dissipating stage.
- Multicell thunderstorms consist of a cluster of single-cell storms. Most of these are not severe, but they can result in considerable precipitation over a local area.



10.3 Severe Thunderstorms

LO 3 List the characteristics of a severe thunderstorm and distinguish among squall lines, mesoscale convective complexes, and supercell thunderstorms.

Key Terms

severe thunderstorm

wind shear

overshooting top

gust front

straight-line winds

roll cloud

shelf cloud

squall line

mesoscale convective complex (MCC)

supercell

mammatus cloud

vertical speed shear

vertical directional shear

mesocyclone

wall cloud

- Severe thunderstorms are capable of producing heavy downpours and flash flooding as well as strong, straight-line winds, large hail, and tornadoes. They are supported by strong vertical wind shear—that is, changes in wind direction and/or speed with increasing height from the surface.
- Downdrafts from the thunderstorm cells reach the surface and spread out to produce an advancing wedge of cold air, called a gust front.
- Squall lines are relatively narrow, elongated bands of thunderstorms that develop in the warm sector of a midlatitude cyclone, usually

ahead of a cold front or dryline.

- A mesoscale convective complex (MCC) consists of many individual thunderstorms that are organized into a large oval to circular cluster that can exceed the size of a state.
- Supercells have tilted, rotating updrafts and are the most likely to produce large hail and tornadoes.

10.4 Lightning and Thunder

LO 4 Explain what causes lightning and thunder.

Key Terms

lightning

sheet lightning

cloud-to-ground lightning

flash

stroke

leader

stepped leader

return stroke

dart leader

thunder

- Lightning equalizes the electrical differences that exist in cumulonimbus clouds by producing a negative flow of current from the region of excess negative charge to the region with excess positive charge, or vice versa.
- The most common type of lightning, often called sheet lightning, occurs within and between clouds. The less common but more dangerous type of lightning is cloud-to-ground lightning.
- The origin of charge separation in clouds, although not fully understood, hinges on the presence of both ice crystals and raindrops in the cloud.

10.5 Tornadoes

LO 5 Describe the structure and basic characteristics of tornadoes.

Key Terms

tornado

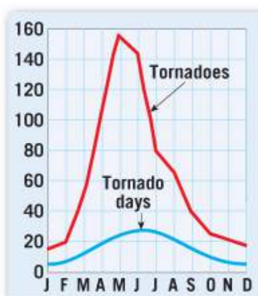
multiple-vortex tornado

- A tornado is a violent windstorm that takes the form of a rotating column of air, or vortex, that extends downward from a cumulonimbus cloud.
- Some tornadoes consist of a single vortex. Multiple-vortex tornadoes contain smaller intense whirls called suction vortices.
- The large pressure gradient associated with tornadoes produces very strong winds.

10.6 Development and Occurrence of Tornadoes

LO 6 Summarize the atmospheric conditions and locations that are favorable to the formation of tornadoes.

- Severe thunderstorms, and hence tornadoes, are most often spawned along the cold front or dryline of a midlatitude cyclone, in association with supercell thunderstorms. Tornadoes can also form in association with tropical cyclones (hurricanes).
- April through June is the period of greatest tornado activity, but tornadoes occur during every month of the year.



10.7 Tornado Destruction and Tornado Forecasting

LO 7 Describe tornado intensity. Distinguish between a tornado watch and a tornado warning, and discuss the role of Doppler radar in the warning process.

Key Terms

Enhanced Fujita Scale (EF Scale)

tornado watch

tornado warning

Doppler radar

dual-polarization (dual-pol) technology

- Most tornado damage is caused by tremendously strong winds. The commonly used guide to tornado intensity is the Enhanced Fujita Scale (EF Scale). A rating on the EF Scale is determined by assessing damage caused by a tornado.
- Because severe thunderstorms and tornadoes are localized, short-lived phenomena, they are among the most difficult weather features to forecast precisely.
- When weather conditions favor tornado formation, a tornado watch is issued. A tornado warning is issued by local offices of the National Weather Service when a tornado has been sighted in an area or is indicated by weather radar.
- Doppler radar technology has greatly advanced the accuracy of tornado warnings. Dual-polarization radar also allows meteorologists to determine the types and sizes of particles in the storm.

Exercises and Online Activities

Mastering Meteorology™

For instructor-assigned homework, test prep resources, and other learning materials, visit **Mastering Meteorology.**

Review Questions

1. Globally, where do thunderstorms frequently occur, and why?
2. What is an ordinary cell thunderstorm, and how does it form?
3. List the three stages in the development of an ordinary cell thunderstorm, and describe the characteristics of each stage.
4. Sketch and label the following features of a severe thunderstorm —overshooting top, lifting condensation level (LCL), anvil, tropopause, shelf cloud.
5. What is a dryline, and what role does it play in the generation of thunderstorms and squall lines?
6. Why does an anvil form in a severe thunderstorm?
7. What is a gust front, and how does it form?
8. Explain the role that a temperature inversion plays in the development of a supercell thunderstorm.
9. Describe a mesocyclone, and explain the mechanism that makes it rotate.
10. Define *microburst*, and describe how it forms.
11. Describe a mesoscale convective complex (MCC). What is the difference between multicell thunderstorms and an MCC?
12. Briefly outline the steps that occur to produce cloud-to-ground lightning.
13. Define *flash*, *leader*, *stroke*, and *return stroke*.
14. What is the source of rotation for a tornado?
15. List the weather conditions that lead to tornado formation.
16. Where is "Tornado Alley," and why do so many tornadoes form there?
17. What does the Enhanced Fujita Scale describe? Which is more destructive, an EF-0 tornado or an EF-5 tornado?
18. Explain how Doppler radar is used to locate possible tornadoes.
19. What is the difference between a tornado watch and a tornado warning?

Give It Some Thought

1. Which one of the locations shown on the accompanying map is more likely to have dryline thunderstorms? Why is this the case?

2. Sinking air warms by compression (adiabatically), yet thunderstorm downdrafts are usually cold. Explain this apparent contradiction.
3. Studies have linked the formation of supercell thunderstorms to the presence of temperature inversions. However, cumulonimbus clouds form in an unstable environment, whereas temperature inversions are associated with very stable atmospheric conditions. Explain the connection between these two phenomena.
4. The table below lists the number of tornadoes reported in the United States by decade. Suggest a possible reason why the total for the 2000s is so much higher than for the 1950s.

Number of U.S. Tornadoes Reported, by Decade

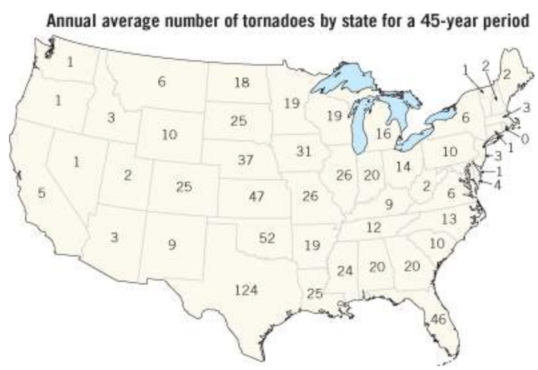
Decade	Number of Tornadoes Reported
1950–1959	4796
1960–1969	6613
1970–1979	8579
1980–1989	8196
1990–1999	12,138
2000–2009	12,914

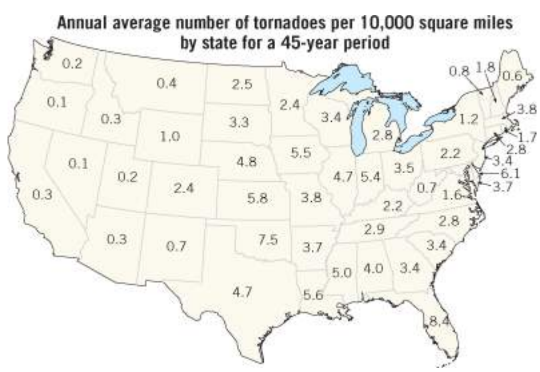
5. Figure 10.29 shows that the number of tornado deaths in the United States in the 2000s fell to fewer than 40 percent of 1950s fatalities, even though there was a significant rise in population during that span. What explains this decline in the death toll?

6. As you will learn in Chapter 11, hurricane intensity is monitored and reported as the storm approaches. However, the intensity of a tornado is not determined and reported until *after* the storm passes. Why is this the case?

By the Numbers

1. If thunder is heard 15 seconds after lightning is seen, about how far away was the lightning stroke?
2. Examine the upper-left portion of Figure 10.24, and determine the percentage of tornadoes that exhibited directions of movement toward the E through NNE.
3. These maps represent two common ways that U.S. tornado statistics are graphically presented to the public. Which four states experience the greatest number of tornadoes? Are these the states with the greatest tornado threat? Which map is most useful for depicting the tornado hazard? Does the map in Figure 10.23 have an advantage over either or both of these maps?





Beyond the Textbook

The Storm Prediction Center (SPC) creates convective outlook maps multiple times a day to show where severe weather is likely. After a severe weather event, a storm damage map displays wind, hail, and tornado damage reports.

1. Making a Severe Weather Prediction

1. What is the current month?
2. Where would you expect to find a risk for severe thunderstorms during this month, if at all?

2. Testing Your Prediction

Go to the SPC Convective Outlook page at http://www.spc.noaa.gov/products/outlook/, and click on the map for "Current Day 1 Outlook" to display the probability for severe thunderstorms today. Hover over Categorical (any severe thunderstorm), Tornado, Wind, or Hail labels to see the probabilities for each of these events. The Categorical map shows the probability from lowest to highest as MRGL (marginal), SLGT (slight), ENH (enhanced), MDT (moderate), and HIGH. The Tornado, Wind, and Hail maps show probability of these events as a percentage. You can click on each image to see a larger version. You can access maps for subsequent days by clicking on the line above the map title.

1. Where is there a risk for severe thunderstorms today? Tornadoes? Wind? Hail?
2. Which areas are at risk for severe weather during Day 2? Day 3? Days 4–8?
3. Does this agree with your prediction in 1?

3. A Severe Weather Outbreak

Go back to the SPC home page. Scroll down to the bottom of the page, and enter the date April 27, 2011 (20110427) in the Start and End Date fields under Retrieve Previous Outlooks. Then click on Retrieve Outlooks. Click on the first Day 1 Convective Outlook link.

1. Where is the greatest risk for severe thunderstorms for this date? Tornadoes? Damaging wind? Large hail?
2. Would you expect severe weather to be highest in this region in April? Why or why not?

In another window, go to the SPC Storm Reports page at http://www.spc.noaa.gov/climo/ and click on the maps to answer the questions.

3. Are there any storm damage reports for today? If so, skim through the list below the map, and briefly summarize the types of damage caused by storms so far today.
4. Go back to the Storm Reports page. Are there any storm damage reports for yesterday? If so, skim through the list, and briefly summarize the types of damage caused by storms yesterday.

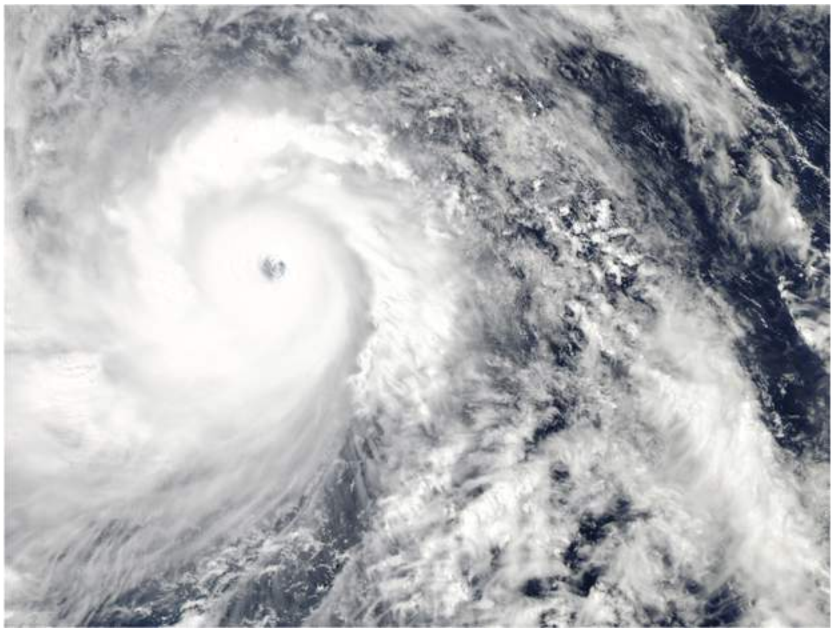
Go back to the Storm Reports page. Under "Storm report data for past days," enter April 27, 2011 (110427) then click Get Data.

5. How many tornado reports? Wind reports? Hail reports?
6. Which state was hardest hit by tornadoes?

Do an Internet search for "Tuscaloosa Alabama 2011 tornado damage images." Examine several of the images.

7. Is it more likely that this was a weak (EF-0 or EF-1) tornado or a strong (EF-4 or EF-5) tornado? Explain your reasoning.

Chapter 11 Hurricanes



Super Typhoon Haiyan, among the strongest storms on record, devastated portions of the central Philippines in November 2013.

Focus on Concepts

Each statement represents the primary learning objective for the corresponding major heading within the chapter. After you complete the chapter, you should be able to:

1. Sketch and describe the basic structure and circulation of a hurricane (11.1).
2. Discuss the conditions that promote hurricane formation and the factors that cause hurricanes to dissipate (11.2).
3. Explain how hurricane intensity is classified and summarize the three broad categories of hurricane destruction (11.3).
4. Summarize the methods used to track and monitor hurricanes (11.4).
5. Describe hurricane forecasting methods and contrast the terms *hurricane watch* and *hurricane warning* (11.5).

The whirling tropical cyclones that occasionally have wind speeds exceeding 300 kilometers (185 miles) per hour are known in the United States as *hurricanes*—the greatest storms on Earth. Hurricanes are among the most destructive of natural disasters. When a hurricane reaches land, it is capable of annihilating low-lying coastal areas and killing thousands of people. It is worth noting, however, that decaying hurricanes provide essential rainfall over areas they cross. Consequently, a resort owner along the Florida coast may dread the coming of hurricane season, whereas a farmer in Japan may welcome its arrival.

11.1 Profile of a Hurricane

LO 1 Sketch and describe the basic structure and circulation of a hurricane.

Many view the weather in the tropics favorably—warm breezes, steady temperatures, and afternoon rains that come as heavy, but brief, tropical showers are typical. Ironically, these relatively tranquil regions occasionally produce some of the most violent storms on Earth—hurricanes. Once formed, these storms can carry severe conditions far from the tropics (Figure 11.1).

Figure 11.1 **Destruction by Hurricane Sandy**

Hurricanes are rapidly rotating storm systems that form over tropical or subtropical oceans and are characterized by low-pressure centers, strong winds, and intense convective thunderstorms that produce heavy rains. In addition to strong winds and heavy rains, hurricanes can produce destructive storm surges and tornadoes. Mature hurricanes average about

600 kilometers (375 miles) across, although they can be twice that diameter. However, size is not necessarily a good indication of hurricane intensity. The pressure gradient, which determines its wind speed, can often be a better measure of potential hurricane damage.

Although many tropical disturbances develop each year, only a few reach hurricane status. An international agreement sets the standard of what qualifies as a hurricane—sustained wind speeds of at least 119 kilometers (74 miles) per hour and a rotary circulation. When it pertains to hurricanes, **sustained winds** are winds speeds determined by averaging observed wind values over a 1-minute period.

> Hurricanes are rapidly rotating storm systems that form over tropical or subtropical oceans and are characterized by strong winds and heavy rains.

Unlike midlatitude cyclones, hurricanes lack contrasting air masses and fronts, and they are not powered by the temperature and moisture contrasts that drive midlatitude storms. Rather, the main source of energy that produces and maintains hurricane-force winds is the huge volume of warm, moist air (and hence *latent heat*) transferred from a warm tropical ocean to the atmosphere above.

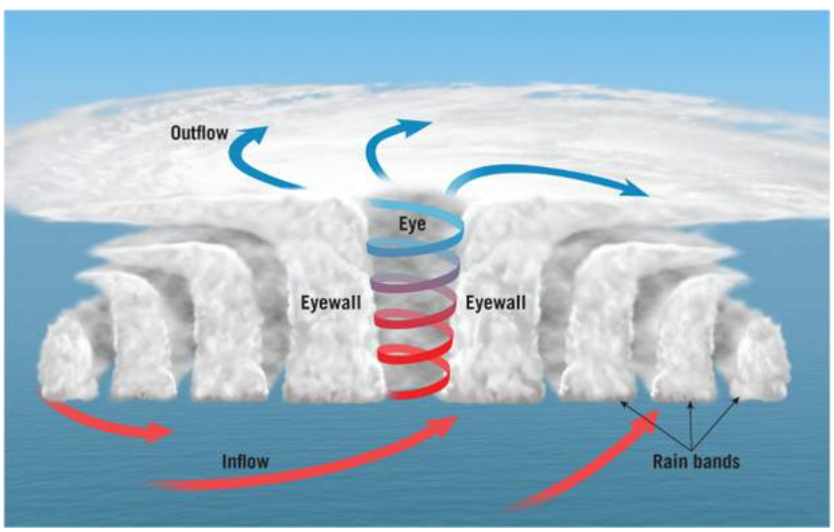
These intense tropical storms are known in various parts of the world by different names. In the northwestern Pacific, they are called *typhoons*; in the southwestern Pacific and the Indian Ocean, they are called *cyclones*. In the following discussion, we will refer to these tropical storms as hurricanes. The term *hurricane* is derived from *Huracan*, a Carib god of evil.

Hurricane Structure

As shown in Figure 11.2, a hurricane consists of the *eye* of the storm located in the center, the *eyewall* that surrounds the eye, and circular *rain bands* that trail away from the eyewall in a spiral fashion. In the Northern Hemisphere, warm, moist air spirals in toward the center in a cyclonic (counterclockwise) pattern, then rises within the eyewall and exits the storm at the top—where it rotates in the opposite direction (anticyclonic airflow). In the center of the hurricane, air sinks to form the eye. The center of the storm, which includes the eye and eye wall, are the warmest parts of the storm at all levels; hence, hurricanes are characterized as "warm core" systems.

Figure 11.2 Structure of a hurricane

Cross section of a hypothetical hurricane. Note that the vertical dimension is greatly exaggerated.



Watch **Video: The Making of a Superstorm**

The Eye

At the very center of the storm is the **eye** of the hurricane, a feature where precipitation ceases and winds subside. The diameter of the eye varies from about 5 to more than 60 kilometers (3 to more than 35 miles). In most hurricanes, the eye is smaller at Earth's surface and widens upward. Near the top of the storm, it may form a relatively large, nearly cloud-free zone surrounded by the upper portions of the eye-wall clouds (Figure 11.3).

Figure 11.3 Hurricane Katrina's eye wall

This photo was taken from a hurricane-hunter aircraft flying through the eye the day before the storm struck the Gulf coast. In this image, the dense cumulonimbus towers of the eye wall surround the blue sky of the eye.

Watch **Animation: Hurricane Wind Patterns**

At the surface, the eye offers a brief, but deceptive, break from the extreme weather occurring in the enormous curving wall clouds surrounding it. The air within the eye gradually descends and heats by compression, making it the warmest part of the storm. Although the eye of strong hurricanes can be characterized by clear blue skies, this is usually not the case because the subsidence is seldom strong enough to produce cloudless conditions. Although the sky appears much brighter in this region, scattered clouds at various levels are common.

The Eye Wall

The doughnut-shaped wall of towering thunderstorms that whirl around the eye of the storm is called the **eye wall** (Figures 11.2 and 11.3). The greatest wind speeds and heaviest rainfall occur in the eye wall, and hence, it is the most destructive part of the storm.

Rain Bands

Surrounding the eye wall are concentric bands of thunderstorm-producing cumulonimbus clouds, called **rain bands**. Because thick high-level clouds usually obscure the rain bands and eye wall, it is difficult for forecasters to use satellite imagery to monitor the storm's interior (Figure 11.2). However, radar can be used for this purpose (see Figure 11.22).

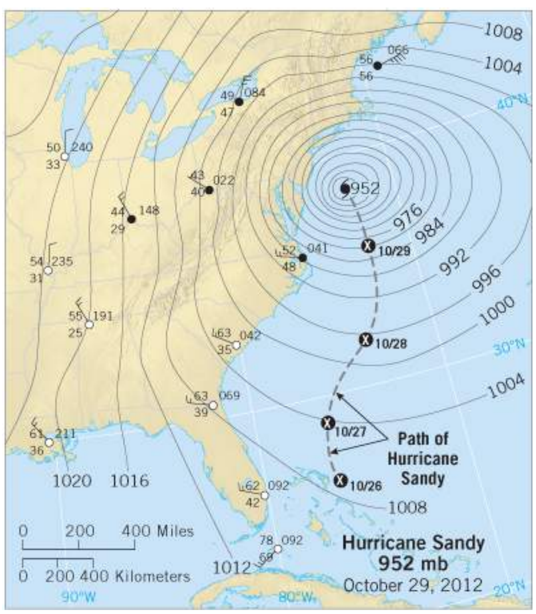
> A hurricane consists of the *eye* of the storm located in the center, the *eye wall* that surrounds the eye, and concentric bands of cumulonimbus clouds called *rain bands*.

Hurricane Circulation

A steep pressure gradient like that shown in Figure 11.4 generates the rapid, inward spiraling winds of a hurricane. As the air moves closer to the center of the storm, its velocity increases. This acceleration is the result of the *law of conservation of angular momentum*. For another example of this principle, consider figure skaters: When they pull their arms inward while whirling on the ice, this action increases their rate of spinning. Similarly, hurricane-strength winds occur primarily in the interior region of a hurricane, a zone about 160 kilometers (100 miles) across in an average storm. The periphery of the storm tends to have gale-force winds—winds that exceed 50 kilometers (30 miles) per hour.

Figure 11.4 Weather map of Hurricane Sandy on October 29

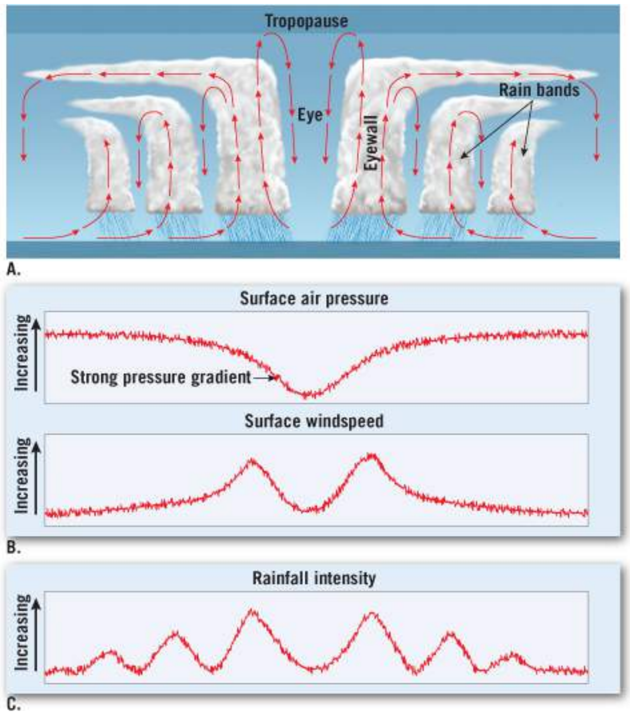
The Xs extending southward from the storm's center show the position of the eye beginning on October 26.



As the inward rush of warm, moist surface air approaches the warm core of the storm, it ascends to form a ring of cumulonimbus towers (Figure 11.5A). Recall that the doughnut-shaped *eye wall* of intense thunderstorms surrounding the center of the storm is where the greatest wind speeds and heaviest rainfall occur. Figure 11.5B shows changes in wind speed and air pressure for a hypothetical hurricane in the Northern Hemisphere. Notice the very steep drop in air pressure as you approach the center of the hurricane, which results in an increase in wind speeds within the eye wall. The relative calm of the eye is also illustrated by a constant pressure in the eye. The size of the cloud bank that forms the eye wall, as compared to the clouds in the rain bands, is reflected in rain intensities shown in Figure 11.5C.

Figure 11.5 **Cross section of an idealized hurricane**

A. This cross-sectional view shows the up-and-down circulation of a hurricane, rather than its strong rotational flow. **B.** This graph illustrates the decrease in surface air pressure from the perimeter toward the eye, which is accompanied by an increase in wind speed. **C.** Rainfall is more intense below the eye wall and decreases outward as the rain bands become less deep.



Once aloft, the airflow is directed away from the storm's center and produces a *cloud shield* that hides the interior of the storm from satellite view. This outward airflow is also responsible for carrying the rising air away from the storm's center, thereby enhancing the inward flow at the surface (see Figure 11.2). Eventually, air leaving the tops of the cumulonimbus towers sinks around the perimeter of the hurricane—producing relatively clear skies and calm conditions that typically surround the storm. Upon reaching the surface, the sinking air is pulled back into the storm. This circulation pattern accounts for most of the air movement associated with hurricanes.

However, the air movement just described cannot account for all of the features we observe in a hurricane. The idealized cross section of a hurricane in Figure 11.5A illustrates the part of the circulation that does not generally involve rotational motion. Notice that some of the air that ascends to form the eye wall eventually encounters the tropopause, which acts like a lid to halt further upward airflow in weather systems. Some of this air is deflected downward *into* the eye and is responsible for the calm conditions we associate with this region of a hurricane.

Some of the air is directed downward *outside* the eyewall. This downdraft eventually reaches the ocean and spreads out. One arm of this circulation system once again flows upward into the eye wall and enhances the updraft that produces the heavy precipitation associated with the eye wall. The other arm moves outward, and is thought to eventually rise and help generate the first rain band. This overturning (up-and-down) air motion may generate other rain bands further from the eye (Figure 11.5A). Rain bands are capable of producing heavy rain and strong winds that are as much as half the strength of those associated with the eye wall.

The atmospheric circulation just described is partially a reflection of the pressure distribution within a hurricane. The pressure gradient and wind speed both increase gradually toward the center of the storm and then increase dramatically near the eye wall, as shown in Figure 11.5B. A steeper pressure gradient equates to stronger winds. Because the eye wall and rain bands are dominated by updrafts, the greatest precipitation occurs in these areas of the storm. The gaps between the rain bands are created by downdrafts consisting of cooler, dryer air and therefore are comparatively rain free (Figure 11.5C).

Concept Checks 11.1

- Define *hurricane*. What other names are used for this storm?
- Compare the winds in the eye with those of the eye wall.

11.2 Hurricane Formation and Decay

LO 2 Discuss the conditions that promote hurricane formation and the factors that cause hurricanes to dissipate.

A hurricane can be thought of as a *heat engine* fueled by thermal energy transferred from a warm ocean surface to the air above, and more important, by latent heat liberated when huge quantities of water vapor condenses to form cloud droplets (or ice crystals). Recall that latent heat is transferred from the ocean to the atmosphere through the process of evaporation.

When this moist surface air rises, it condenses to form clouds. Condensation releases the latent heat extracted from the ocean into the surrounding air, which in turn warms the air and provides buoyancy for its upward flight. The result is lower air pressure near Earth's surface, which encourages inflow of even more warm, humid air. A large quantity of warm, moist air is required to get this "storm engine" started, and a continuous supply is needed to keep it going. In fact, the amount of heat energy converted to energy of motion during one day by a mature hurricane is equivalent to 200 times the daily energy consumed worldwide. Just like the engine in a car, a hurricane extracts energy from a source and converts it into motion.

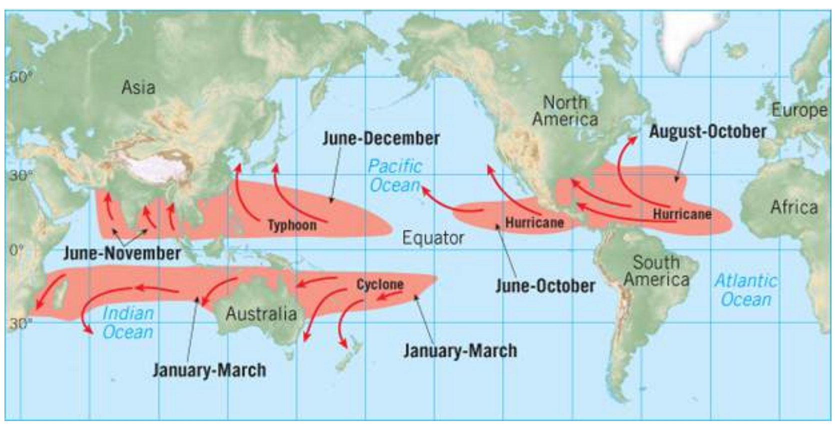
> Latent heat is the main energy source for the destructive winds of a hurricane.

Where Do Hurricanes Form?

Most hurricanes form between the latitudes of 5° and 30° over all tropical oceans, with the exceptions of the South Atlantic and eastern South Pacific oceans, where they rarely occur (Figure 11.6). The western North Pacific has the greatest number of storms, averaging 20 per year. Fortunately for those living in the coastal regions of the southern and eastern United States, only about six hurricanes, on average, develop each year in the warm sector of the North Atlantic.

Figure 11.6 Regions of hurricane formation

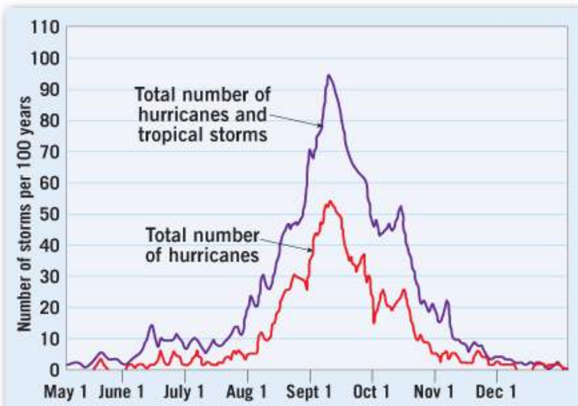
This world map shows the regions where most hurricanes form, as well as their principal months of occurrence and the most common tracks they follow.



As the graph in Figure 11.7 illustrates, hurricanes most often form in late summer and early fall. It is during this span that sea-surface temperatures reach 27°C (80°F) or higher and are thus able to provide the necessary heat and moisture to the air. This requirement for warm ocean waters explains why hurricanes only rarely form over the relatively cool waters of the South Atlantic and the eastern South Pacific. For the same reason, few hurricanes form poleward of 30° latitude (see Figure 11.6). Further, although water temperatures are sufficiently high, hurricanes rarely form within 5° of the equator because the Coriolis force is too weak in that region to initiate the necessary rotary motion.

Figure 11.7 Frequency of tropical storms and hurricanes in the Atlantic basin

This graph shows the number of storms to be expected, calculated over a span of 100 years. The period from late August through October is clearly the most active.



Unlike severe thunderstorms, which require vertical wind shear, hurricanes do not develop where the winds aloft are strong. (Recall that the vertical wind shear is the change in wind speed or direction with height above the surface.) For a hurricane to form and intensify, it must have an organized central structure consisting of vertically aligned cumulonimbus towers. Strong wind shear can disrupt the organization of the storm's internal structure. In addition, strong winds aloft tend to disperse the latent heat released from cloud tops—heat that is essential for continued storm growth and development.

> The criteria necessary for hurricane formation include a large area of water warmer than 80°F, location at least 5° latitude from the equator, and weak winds aloft.

Formation of Tropical Disturbances

Many tropical storms achieve hurricane status in the western parts of oceans, but their origins often lie far to the east. Nearly all tropical storms begin as disorganized arrays of clouds and thunderstorms, called **tropical disturbances**. These areas of stormy weather exhibit weak pressure gradients and little or no rotation.

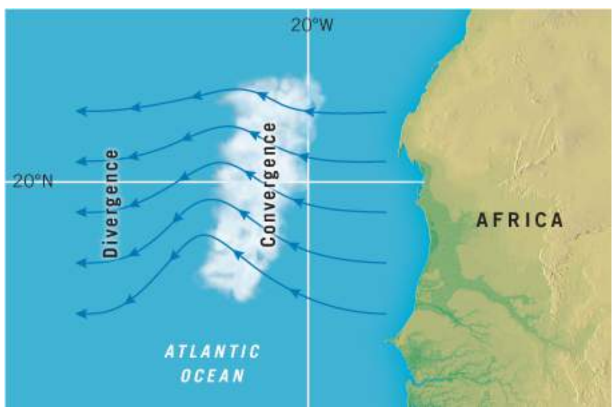
Several different environments can trigger a tropical disturbance. They are sometimes initiated by the powerful convergence and lifting associated with the intertropical convergence zone (ITCZ). Others form when a cold front that originated in the middle latitudes intrudes into the tropics. Most tropical disturbances, however, are triggered by *easterly waves*.

Easterly Waves

Tropical disturbances that produce most of the strongest hurricanes that threaten North America usually begin as large undulations or ripples in the trade winds known as **easterly waves (or tropical waves)**, so named because they gradually move from east to west. Figure 11.8 illustrates an easterly wave. The lines on this simple map are not isobars. Rather, they are *streamlines*, lines drawn parallel to the wind direction used to depict surface airflow. Streamlines are helpful because they show where surface winds converge and diverge.

Figure 11.8 Easterly wave in the subtropical North Atlantic

Streamlines show low-level airflow. Tropical disturbances are associated with the convergent flow of the easterly wave.



To the east of the wave axis, the streamlines get progressively closer together, indicating that the surface flow is converging. Recall from Chapter 4 that convergence encourages air to rise and form clouds. As a result, tropical disturbances form on the east side of an easterly wave.

> Many tropical disturbances begin as large undulations in the trade winds known as easterly waves.

Why Tropical Disturbances Dissipate

More than 90 percent of tropical disturbances die out without ever organizing into more powerful storms. One condition that inhibits further development is a temperature inversion. Recall that a strong inversion diminishes the ability of air to rise and thus hinders the development of strong thunderstorms. In tropical oceans, most temperature inversions are the result of subsidence within subtropical high-pressure systems, which are dominant features in all large ocean basins. For example, the Bermuda/Azores high is a subtropical high situated in the subtropics over the North Atlantic (see Figure 7.11).

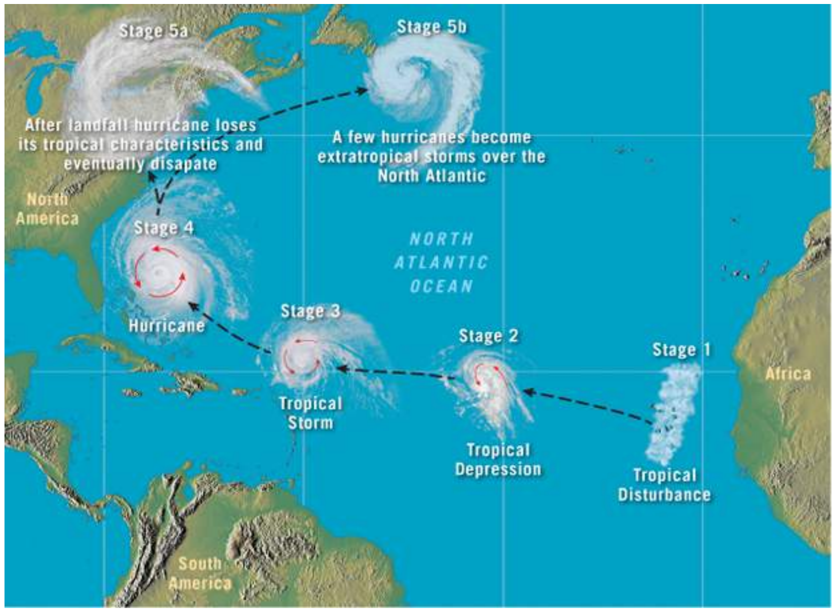
Tropical disturbances must also be supported by a steady outflow (divergence) of air from the top of the storm. Without outward flow near the top, the inflow at lower levels would soon raise surface pressures and thwart further storm development. In addition, when winds aloft are too strong, they can prevent the tropical disturbance from developing an organized central core.

From Tropical Disturbance to Hurricane

What happens when conditions favor hurricane development? As latent heat is released from the clusters of thunderstorms that comprise a tropical disturbance, the center of the disturbance gets warmer. As a result, air density decreases and surface pressure drops, creating a region of weak low pressure and cyclonic circulation. As pressure drops at the storm's center, the pressure gradient steepens. In response, surface winds strengthen and bring in additional moisture to nurture storm growth. This additional water vapor condenses and releases even more latent heat, which causes a further increase in buoyancy—and the cycle continues.

Under these conditions, a tropical depression will grow from a cluster of thunderstorms into an organized system (Figure 11.9). Meteorologists can identify this phase in the storm's development because the entire group of thunderstorms begins to spin or rotate. An organized rotating system of thunderstorms is called a **tropical depression**, named for its "depressed," or low, air pressure in the center. Low pressure creates winds that rush in to the storm's center—the lower pressure results in stronger winds.

Figure 11.9 **Illustration showing stages in the evolution of a typical North Atlantic hurricane**



Watch **Video: The 2005 Hurricane Season**

When a tropical depression strengthens such that its sustained winds are between 63 and 119 kilometers (39 and 74 miles) per hour, the cyclone is termed a **tropical storm** (Figure 11.9). In the Northern Hemisphere, tropical storms have a well-defined counterclockwise rotation and strong winds indicative of a powerful tropical cyclone. It is during this phase that an alphabetically ordered name is assigned (Andrew, Katrina, Sandy, and so on). Each year, between 80 and 100 tropical storms develop around the globe. Of these, usually half or more eventually reach hurricane status. Recall that tropical cyclones are called *hurricanes* only when their winds reach 119 kilometers (74 miles) per hour or more. If the tropical storm becomes a hurricane, the name remains the same (Box 11.1).

Box 11.1

Naming Tropical Storms and Hurricanes

Tropical storms are named to provide ease of communication between forecasters and the general public regarding forecasts, watches, and warnings. Because two or more tropical storms and/or hurricanes can occur in the same ocean basin at the same time, names reduce the confusion about which storm is being described.

During World War II, tropical storms were informally assigned women's names (perhaps after wives and girlfriends) by U.S. Army Corps and Navy meteorologists who were monitoring storms over the Pacific. From 1950 to 1952, tropical storms in the North Atlantic were identified by the phonetic alphabet—Abel, Baker, Charlie, and so forth. In 1953, the U.S. Weather Bureau (now the National Weather Service) switched to women's names. The practice of using feminine names continued until 1978, when a list containing both male and female names was adopted for tropical cyclones in the eastern Pacific.

The World Meteorological Organization (WMO) created our current system of naming tropical storms. The names used for Atlantic, Gulf of Mexico, and Caribbean hurricanes are shown in Table 11.A. The six lists of names are ordered alphabetically but do not include names that begin with the letters Q, U, X, Y, and Z because of the scarcity of names beginning with those letters. When a tropical depression reaches tropical storm status, it is assigned the next unused name on the list.

The list of names for Atlantic storms is "recycled" following each 6-year cycle. However, names of particularly noteworthy hurricanes are retired so that they won't be confused with future storms that would otherwise carry the same name. For example, following the hurricane seasons of 2015 and 2016, the names Matthew, Otto, Erika, and Joaquin were retired. On the lists for 2021 and 2022, Martin, Owen, Elsa, and Julian replace them.

Apply What You Know

1. Why are tropical storms named?
2. What organization is responsible for creating the lists of names?

Table 11.A Tropical Storm and Hurricane Names for the Atlantic, Gulf of Mexico, and Caribbean Sea*

2017	2018	2019	2020	2021	2022
Arlene	Alberto	Andrea	Arthur	Ana	Alex
Bret	Beryl	Barry	Bertha	Bill	Bonnie
Cindy	Chris	Chantal	Cristobal	Claudette	Colin
Don	Debby	Dorian	Dolly	Danny	Danielle
Emily	Ernesto	Erin	Edouard	Elsa	Earl
Franklin	Florence	Fernand	Fay	Fred	Fiona
Gert	Gordon	Gabrielle	Gonzalo	Grace	Gaston
Harvey	Helene	Humberto	Hanna	Henri	Hermine
Irma	Isaac	Imelda	Isaias	Ida	Ian
Jose	Joyce	Jerry	Josephine	Julian	Julia
Katia	Kirk	Karen	Kyle	Kate	Karl
Lee	Leslie	Lorenzo	Laura	Larry	Lisa
Maria	Michael	Melissa	Marco	Mindy	Martin
Nate	Nadine	Nestor	Nana	Nicholas	Nicole
Ophelia	Oscar	Olga	Omar	Odette	Owen
Philippe	Patty	Pablo	Paulette	Peter	Paula
Rina	Rafael	Rebekah	Rene	Rose	Richard
Sean	Sara	Sebastien	Sally	Sam	Shary
Tammy	Tony	Tanya	Teddy	Teresa	Tobias
Vince	Valerie	Van	Vicky	Victor	Virginie
Whitney	William	Wendy	Wilfred	Wanda	Walter

*If the entire alphabetical list of names for a given year is exhausted, the naming system moves on to letters of the Greek alphabet (alpha, beta, gamma, and so on).

> A tropical depression can strengthen into a tropical storm, which can develop into a hurricane.

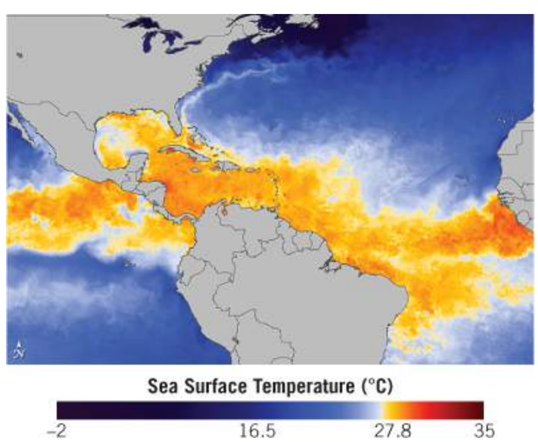
Hurricane Decay

Hurricanes diminish in intensity when they (1) move over ocean waters that are too cold to supply adequate latent heat; (2) make landfall; or (3) reach a location where upper-level winds are strong.

Many hurricanes approaching North America from the southeast are turned toward the northeast by the steering effect of upper-level flow. This change of direction carries the storms toward higher latitudes, where ocean surface temperatures can be significantly below 27°C (80°F) (Figure 11.10). As a result, the hurricane loses it tropical characteristics, mainly its warm central core composed of towering cumulonimbus clouds. The remnant low-pressure system may remain for several days before losing its identity.

Figure 11.10 Sea-surface temperatures

Among the necessary ingredients for a hurricane is warm ocean temperatures above 27°C (80°F). This color-coded satellite image from June 1, 2010, shows sea-surface temperatures at the beginning of hurricane season. When a hurricane moves poleward of the brightly colored area, it begins to lose its source of energy—latent heat.



> Hurricanes diminish when they encounter cold water, make landfall, or reach a location where upper-level winds are strong.

You might have wondered . . .

When is hurricane season?

Hurricane season occurs at different times in different parts of the world. The Atlantic hurricane season officially extends from June through November. More than 97 percent of tropical activity in that region occurs during this 6-month span. The "heart" of the season is August through October (see Figure 11.7), when about 90 percent of hurricane days occur, with peak activity in early to mid September.

When a hurricane moves onto land, its wind speeds usually drop dramatically, but the storm may still produce abundant precipitation for the next several days (see Figure 11.9). The most important reason for the storm's demise is the fact that its energy source of warm, moist air is gradually cut off. Without an adequate supply of water vapor, condensation and the release of latent heat diminish. In addition, surface roughness increases as the storm moves over land, causing surface wind speeds to fall rapidly. This friction, along with the resulting slower wind speeds, causes the air to move more directly into the center of these low-pressure systems. This change in wind direction "fills" the storm and helps eliminate the strong pressure gradient. As a result, the storm gradually dissipates.

Some hurricanes make landfall (or pass close to the east coast of North America) and encounter a cold air mass (cold front), which causes the storm to evolve into an extratropical cyclone (midlatitude cyclone). Such was the case when Hurricane Sandy made landfall on October 29, 2012, over northern New Jersey. By the time Sandy was onshore, it had lost its tropical characteristics and was described by the NWS as a strong nor'easter (see Chapter 9). Within two days, Sandy was centered over western Pennsylvania, where it was downgraded to a weak low-pressure system.

Although less common, a few hurricanes become extratropical storms without ever making landfall (see Figure 11.9). These systems are often carried by the westerlies toward Europe, where they produce foul weather.

Recall that hurricanes need light winds aloft. If a hurricane encounters strong winds aloft, the convective circulation (thunderstorms) near the center of the storm can be disrupted, reducing the efficiency of the storm's heat engine. As a result, the storm will lose its strong rotational motion and begin to dissipate.

Concept Checks 11.2

- What factor may inhibit the strengthening of tropical disturbances?
- Distinguish *tropical depression*, *tropical storm*, and *hurricane*.
- List the major factors that cause a hurricane to diminish in strength.

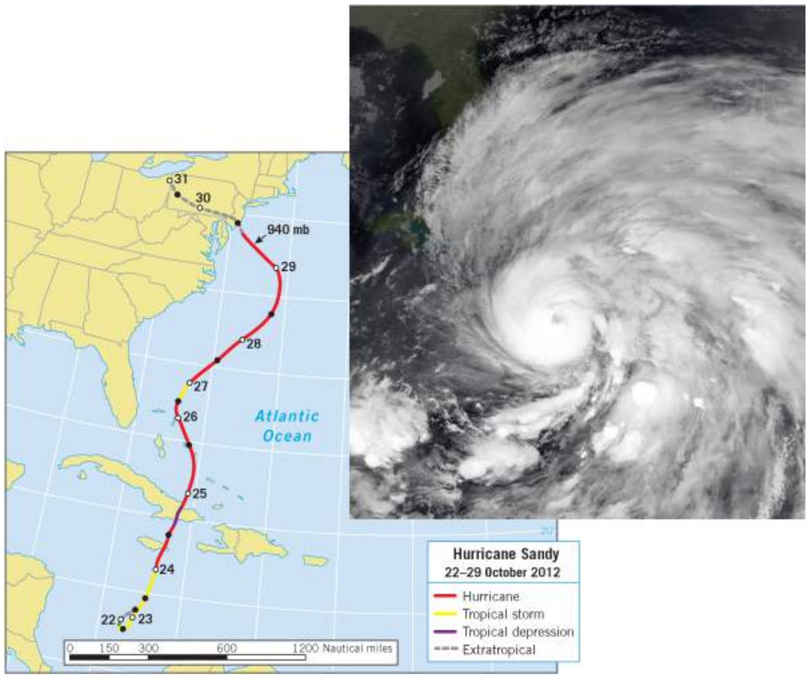
11.3 Hurricane Destruction

LO 3 Explain how hurricane intensity is classified and summarize the three broad categories of hurricane destruction.

Although hurricanes are tropical or subtropical in origin, their destructive effects can be experienced far from where they originate (Figure 11.11). For example, in October 2012 Hurricane Sandy affected the entire eastern seaboard from Florida to Maine. Damages were estimated at $65 billion, the second costliest hurricane in U.S. history after Katrina in 2005. Destruction was especially great in New Jersey and New York (see Figure 11.1).

Figure 11.11 **Hurricane Sandy**

This satellite image shows the storm on October 26, 2012, when it was located off the east coast of Florida. The storm inflicted most of its destruction to property far from the subtropics, in New York and New Jersey.



The vast majority of hurricane-related deaths and damage are caused by relatively infrequent yet powerful storms. Table 11.1 lists the deadliest hurricanes to strike the United States between 1900 and 2016. The storm that pounded an unsuspecting Galveston, Texas, in 1900 was not just the deadliest U.S. hurricane ever but the deadliest natural disaster *of any kind* to affect the United States. Of course, the deadliest and most costly storm in recent memory occurred in August 2005, when Hurricane Katrina devastated the Gulf coast of Louisiana, Mississippi, and Alabama. Although hundreds of thousands of residents fled before Katrina made landfall, thousands of others were caught by the storm.

Table 11.1 **The 10 Deadliest Hurricanes to Strike the Continental United States, 1900–2016**

Rank	Hurricane	Year	Category	Deaths
1.	Texas (Galveston)	1900	4	8000*
2.	Southeastern Florida (Lake Okeechobee)	1928	4	2500–3000
3.	Katrina	2005	4	1833
4.	Audrey	1957	4	At least 416
5.	Florida Keys	1935	5	408
6.	Florida (Miami)/ Mississippi/Alabama/ Florida (Pensacola)	1926	4	372
7.	Louisiana (Grande Isle)	1909	4	350
8.	Florida Keys/South Texas	1919	4	287
9. (tie)	Louisiana (New Orleans)	1915	4	275
9. (tie)	Texas (Galveston)	1915	4	275

Source: National Weather Service/National Hurricane Center.
*This number may actually have been as high as 10,000–12,000.

Saffir-Simpson Scale

Based on the study of past storms, the **Saffir-Simpson scale**, also known as the *Saffir-Simpson Hurricane Wind Scale*, was established to rank the relative intensities of hurricanes (Figure 11.12). Predictions of hurricane severity and damage are usually expressed in terms of this scale. When a tropical storm becomes a hurricane, the National Hurricane Center assigns it a scale (category) number. The assigned category, based on observed sustained wind speeds, is viewed as an estimate of the amount of damage a storm would cause if it were to make landfall without changing size or strength. As conditions change, the Hurricane Center re-evaluates the category of a storm. Use of the Saffir–Simpson scale to rate the disaster potential of a hurricane allows for planning and implementing appropriate precautions.

Figure 11.12 Saffir-Simpson Hurricane Wind Scale

Saffir–Simpson Hurricane Wind Scale*

Category (Scale numbers)	Winds (km/hr)	Damage at landfall
1	119–153	Minimal
2	154–177	Moderate
3	178–209	Extensive
4	210–250	Extreme
5	>250	Catastrophic

*The Saffir-Simpson Hurricane Scale became the Saffir-Simpson Hurricane Wind Scale in May 2010.

> The Saffir-Simpson scale is used to rank hurricanes, with category 1 being the weakest and category 5 the strongest hurricane.

A rating of 5 on the scale represents the strongest storm possible, and a 1 is least severe. Storms classified as category 5 are rare—only three storms this powerful are known to have hit the continental United States:

Andrew struck Florida in 1992, Camille pounded Mississippi in 1969, and a Labor Day hurricane struck the Florida Keys in 1935.

Sometimes the intensity of a storm is described using terms such as “major hurricane” or “super typhoon.” The National Hurricane Center uses *major hurricane* to describe a storm that reaches maximum sustained 1-minute surface winds of at least 178 kilometers (111 miles) per hour, meaning that it is at least a category 3 storm. The U.S. Joint Typhoon Warning Center uses *super typhoon* for storms in the western Pacific that have sustained winds of at least 210 kilometers (131 miles) per hour, equivalent to at least a category 4 on the Saffir–Simpson scale. Super Typhoon Haiyan, which struck the Philippines in November 2013, is examined in Severe & Hazardous Weather Box 11.2, later in the chapter.

> Damage caused by hurricanes can be divided into three classes: (1) storm surge, (2) wind damage, and (3) inland flooding.

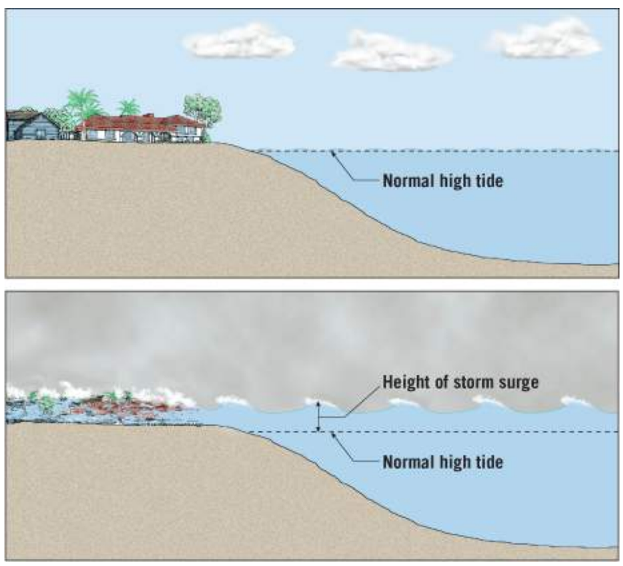
Damage caused by hurricanes can be divided into three types: (1) storm surge, (2) wind damage, and (3) inland freshwater flooding.

Storm Surge

Without question, the most devastating damage in a coastal zone is caused by a hurricane's storm surge. A **storm surge** is a dome of water often 80 kilometers (50 miles) wide that sweeps across the coast near the point where the eye makes landfall. When all wave activity is smoothed out, the storm surge is a measure of the height of the water above normal high tide level (Figure 11.13).

Figure 11.13 Storm surge

Superimposed upon high tide, a storm surge can devastate a coastal area. The worst storm surges occur in coastal areas where there is a very shallow and gently sloping continental shelf extending from the beach. The Gulf coast is such a place.

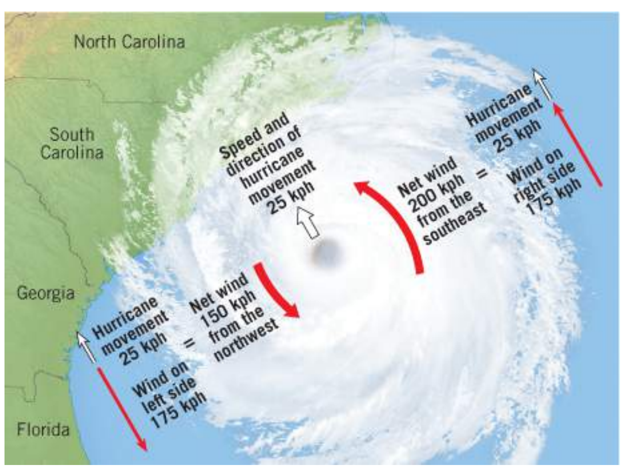


> Storm surge is the rising water level caused predominantly by wind blowing water onshore.

The piling up of ocean water by strong onshore winds is the most important factor responsible for the development of a storm surge. (Low pressure at the center of a hurricane will cause a higher storm surge, but this effect is relatively small.) The hurricane's winds gradually but steadily push water toward the shore, causing sea level to elevate while also churning up violent wave activity. As a hurricane advances toward the coast in the Northern Hemisphere, a storm surge is usually most intense on the right side of the eye when looking in the direction the hurricane is moving—the side where the winds are blowing *toward* the shore. In addition, the forward movement on this side of the hurricane also contributes to the storm surge. Figure 11.14 illustrates a hurricane with peak winds of 175 kilometers per hour that is moving toward the shore at 50 kilometers per hour. In this case, the net wind speed on the right side of the advancing storm is 225 kilometers per hour. On the left side, the hurricane's winds are blowing opposite the direction of storm movement, so the net winds are *away* from the coast, at 125 kilometers per hour. Along the shore facing the left side of the oncoming hurricane, the water level may actually decrease as the storm makes landfall.

Figure 11.14 **Wind speeds of an approaching hurricane**

Winds associated with a Northern Hemisphere hurricane that is advancing toward the coast. Storm surge will be greatest along the part of the coast hit by the right side of the advancing hurricane when looking in the direction the hurricane is moving.



Some of the worst surges occur in places like the Gulf of Mexico, where the continental shelf is very shallow and gently sloping (Figure 11.15). In addition, local features such as narrow inlets can restrict flow and cause surge heights to double in some areas.

Figure 11.15 Aftermath of Hurricane Ike

In mid-September 2008, the eye of the storm passed directly over Galveston, Texas. The extraordinary storm surge caused much of the damage pictured here at Crystal Beach.

In the delta region of Bangladesh, most of the land is less than 2 meters (6.5 feet) above sea level. When a storm surge superimposed on normal high tide inundated that area on November 13, 1970, the official death toll was 200,000; unofficial estimates ran to 500,000. It was one of the worst natural disasters of modern times. As sea level continues to rise in coming decades, low-lying, densely populated coastal areas will become even more vulnerable to the destructive effects of storm surge.

Eye on the Atmosphere 11.1

This hurricane occurred in the Atlantic in 2004.

Apply What You Know

1. Did the storm occur in the North Atlantic or the South Atlantic? How did you figure this out?
2. Did the storm more likely occur in March or September?

Wind Damage

Destruction caused by wind is perhaps the most obvious cause of hurricane damage. Debris such as signs, roofing materials, and small items left outside become dangerous flying missiles in hurricanes. Mobile homes are particularly vulnerable. High-rise buildings are also susceptible to hurricane-force winds, with upper floors most vulnerable because wind speeds usually increase with height.

Recent research suggests that people should stay below the 10th floor but remain above any floors at risk for flooding. In regions with good building codes, wind damage is usually not as catastrophic as storm-surge damage. However, hurricane-force winds affect a much larger area than storm surge. For example, in 1992 it was largely the winds associated with Hurricane Andrew that produced more than $25 billion in damage in southern Florida and Louisiana.

Hurricanes may also produce tornadoes that contribute to the storm's destructive power. Studies have shown that more than half of the hurricanes that make landfall produce at least one tornado. In 2004, the number of tornadoes associated with tropical storms and hurricanes was extraordinary. Tropical Storm Bonnie and five landfalling hurricanes—Charley, Frances, Gaston, Ivan, and Jeanne—produced nearly 300 tornadoes that affected the southeast and mid-Atlantic states (Table 11.2).

Table 11.2 **Number of Tornadoes Spawned by Hurricanes and Tropical Storms in the United States, 2004**

Tropical Storm Bonnie	30
Hurricane Charley	25
Hurricane Frances	117
Hurricane Gaston	1
Hurricane Ivan	104
Hurricane Jeanne	16

Hurricanes that make landfall may produce numerous destructive tornadoes.

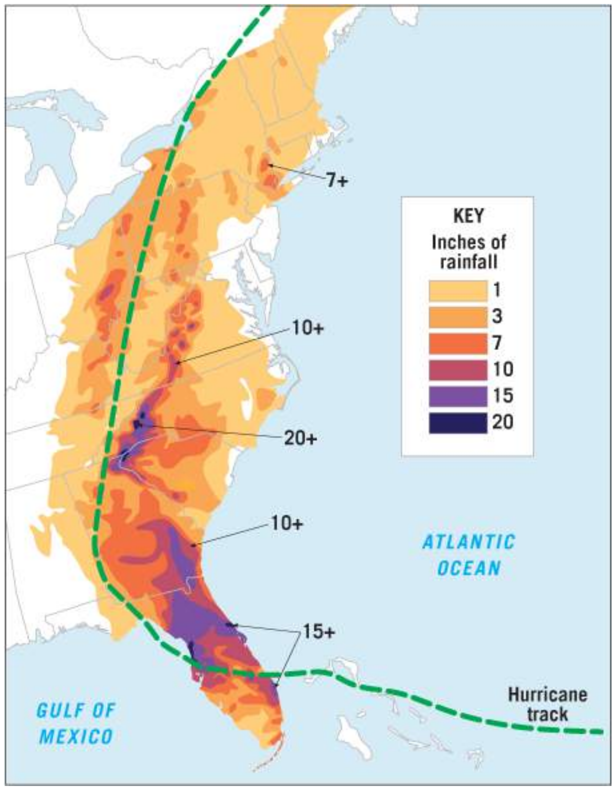
Heavy Rains and Inland Flooding

The torrential rains that accompany most hurricanes represent a third significant threat—flooding. In fact, flooding holds the greatest risk for people living inland. Rainfall amounts are related not necessarily to the intensity of a tropical storm, but more often to the storm's size and rate of movement. Larger and slower-moving storms produce the most precipitation. For example, Hurricane Harvey made landfall in southern Texas on August 25, 2017, then remained over the area for days. The region received 40-61 inches of rain, breaking U.S. records for rainfall in southeast Texas and southwest Louisiana.

Further, elevated terrains greatly enhance rainfall amounts. In addition to generating 117 tornadoes, Hurricane Frances (2004) produced extensive flooding from southern Florida to as far north as Pittsburgh, Pennsylvania. Frances dropped significant precipitation in Florida, Georgia, Alabama, and North and South Carolina, as shown in Figure 11.16. Some parts of Florida received more than 15 inches of precipitation, while schools were closed in 56 counties in Georgia. The heaviest amount of rainfall was recorded at Mount Mitchell, North Carolina, high in the Appalachian Mountains, where 24 inches of precipitation fell.

Figure 11.16 **Heavy rains and inland flooding**

Hurricane Frances (2004) produced extensive flooding from southern Florida to as far north as Pittsburgh, Pennsylvania.



Concept Checks 11.3

- What is the purpose of the Saffir–Simpson scale?
- List the three broad categories of hurricane damage.
- Which category of hurricane damage causes the most destruction?

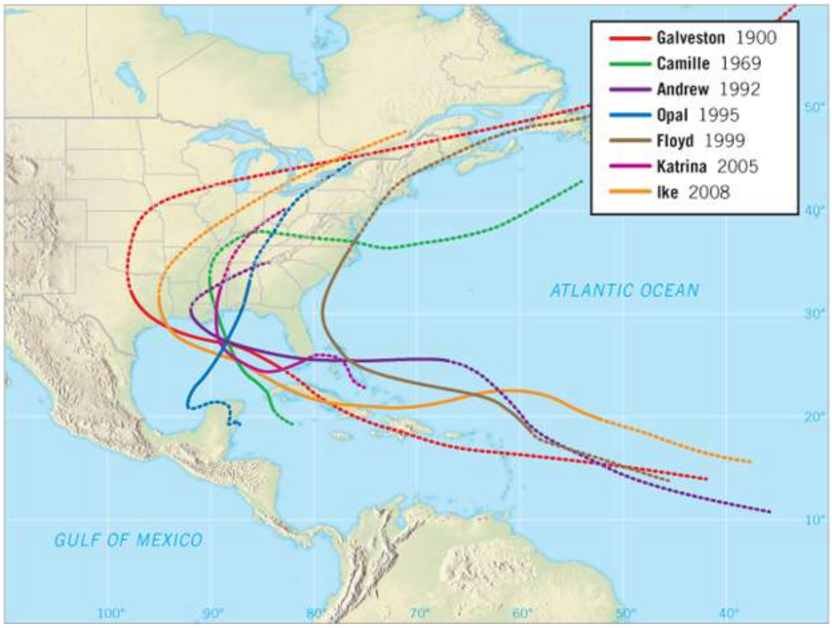
11.4 Tracking and Monitoring Hurricanes

LO 4 Summarize the methods used to track and monitor hurricanes.

Figure 11.17 shows the paths followed by some notable Atlantic hurricanes. Many others continued on a straighter path and made landfall in Mexico, while still others turned north and followed the eastern coastline of the United States, never making landfall. What determines these tracks? Tropical storms can be thought of as being steered by the surrounding airflow throughout the depth of the troposphere—a movement that has been likened to a leaf being carried along by the currents in a stream. Thus, the movement of a hurricane is largely determined by the larger circulation pattern in which it is embedded. Stated another way, the storm is being "steered" by the airflow that surrounds it.

Figure 11.17 **Storm tracks**

This map shows a variety of tracks for some memorable hurricanes. The solid portion of each line indicates when a storm had hurricane status.



The movement of a tropical storm is initially controlled by trade winds at lower latitudes, which push the storm toward the west (Figure 11.17). Steering winds aided by the Coriolis force then turns the storm's track to the right—or *north* in the Northern Hemisphere. As the storm moves northward into the middle latitudes, it is swept along by westerlies.

When strong steering winds are present, the path of a storm looks like the letter "C", as illustrated by most of the storm tracks in Figure 11.17. If strong steering winds are not present, then the track of a storm can be erratic and difficult to predict (see Figure 11.11). Often it is difficult to determine whether a storm will curve back out to sea or continue on its current path and make landfall.

> A typical path for a hurricane looks like the letter “C” but if steering winds are weak, the path can be very erratic.

Because the tropical and subtropical regions that spawn hurricanes consist of enormous areas of open ocean, conventional observational tools are inadequate to track and monitor hurricane movement. The need for meteorological data from these vast regions is now met primarily by satellites.

The Role of Satellites

Satellites are very useful for tracking the motion of a hurricane, but it is much more difficult to determine a tropical cyclone's internal wind speed. Two methods of using satellite-acquired data to monitor hurricane intensity have been developed. One technique involves using instruments aboard a satellite to estimate wind speeds within a storm. A second method uses instruments to identify areas of extraordinary cloud and precipitation development in the eye wall of an approaching hurricane.

> Satellites are used to track the location of a hurricane, estimate its speed, and create a three-dimensional map of storm intensity.

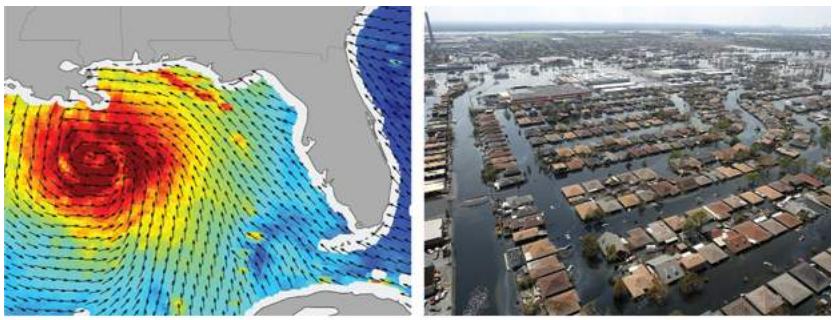
Estimating Wind Speeds

In the absence of direct wind speed data, instruments called **radar scatterometers** are used to measure the strength of a storm's winds. These instruments are particularly important in monitoring typhoons and cyclones in the Pacific, where aircraft cannot effectively observe such a vast area. Scatterometers work on the principle that winds roughen the ocean's surface—larger ocean waves mean higher wind speeds. The instrument detects differences in how microwave radiation is scattered by the ocean surface. A complex model is then used to estimate the speed of the winds responsible for that amount of roughness.

The image in Figure 11.18A was produced from data obtained from a radar scatterometer on NASA's retired *QuickSCAT* satellite, and shows the wind field of Hurricane Katrina (2005). Wind direction is shown with black arrows and wind speeds are shown with colored patterns. The eye wall is shown as a dark red concentric ring near the center of the storm, indicating that Katrina was a classic tropical storm with a symmetrical wind field that whipped around a nearly circular low-pressure center. Unfortunately, Katrina's powerful winds slammed into Gulfport and Biloxi, Mississippi, devastating both cities. Katrina's heavy rains and strong winds also caused flooding in several cities including New Orleans, cut electric power to millions, and tore apart densely populated coastlines (Figure 11.18B).

Figure 11.18 **Measuring hurricane wind speed and potential destruction**

A. Data obtained from a radar scatterometer on NASA's retired *QuickSCAT* satellite that shows the wind field of Katrina (2005). Wind direction is shown with black arrows, and wind speeds are shown with colored patterns, with darker shades indicating stronger winds. **B.** Flooded neighborhood in New Orleans, Louisiana, caused by Hurricane Katrina.



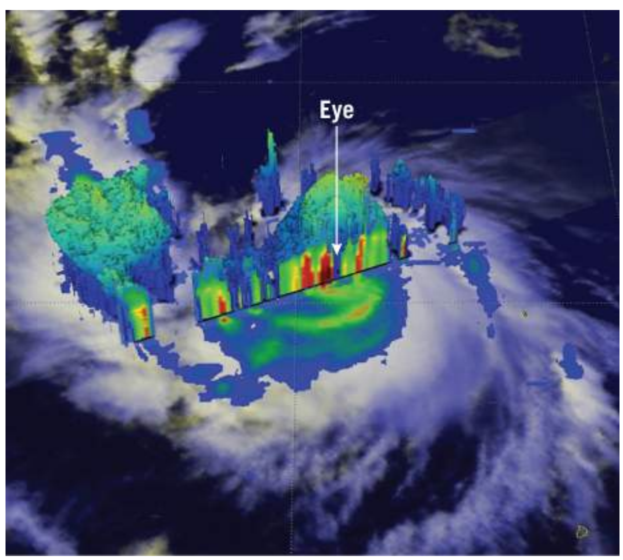
A. B.

Monitoring Rainfall and Cloud Heights

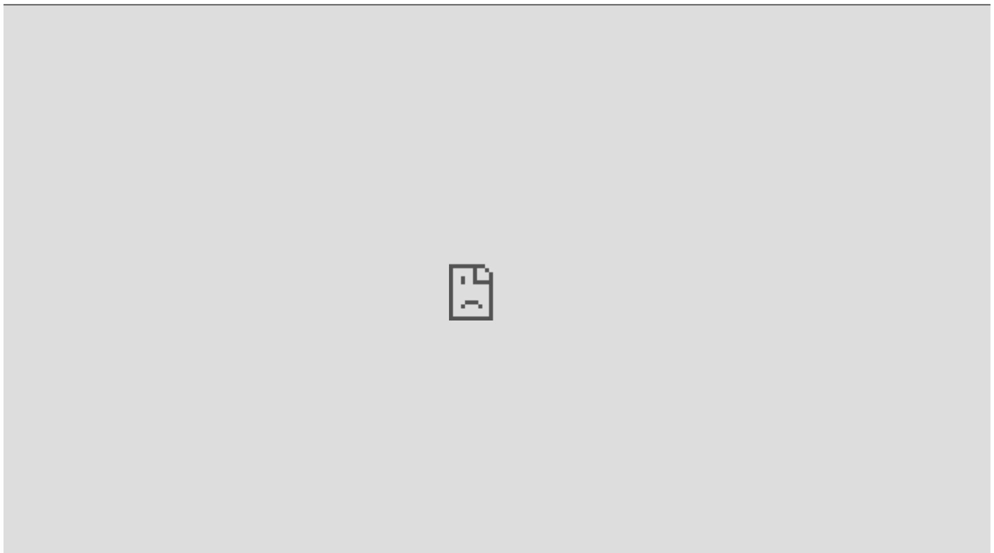
Knowing rainfall patterns and cloud heights in different parts of a hurricane is beneficial to forecasters because it helps determine the strength of the storm. The *Global Precipitation Mission* (GPM) uses the GPM core satellite for this purpose. As shown in Figure 11.19, the satellite's dual-frequency precipitation radar provided a three-dimensional map of Hurricane Seymour's structure on October 25, 2016. The GPM's radar revealed that rain was falling at the extreme rate of 16.6 centimeters (6.6 inches) per hour in the red-colored rain bands located south (left) of the storm's eye.

Figure 11.19 **GPM core satellite provided this 3-D map of Hurricane Seymour's structure**

The GPM's radar revealed that rain was falling at the extreme rate of 16.6 centimeters (6.6 inches) per hour in the red-colored rain bands located south (left) of the eye.



Watch **Video: Hot Towers and Hurricane Intensification**



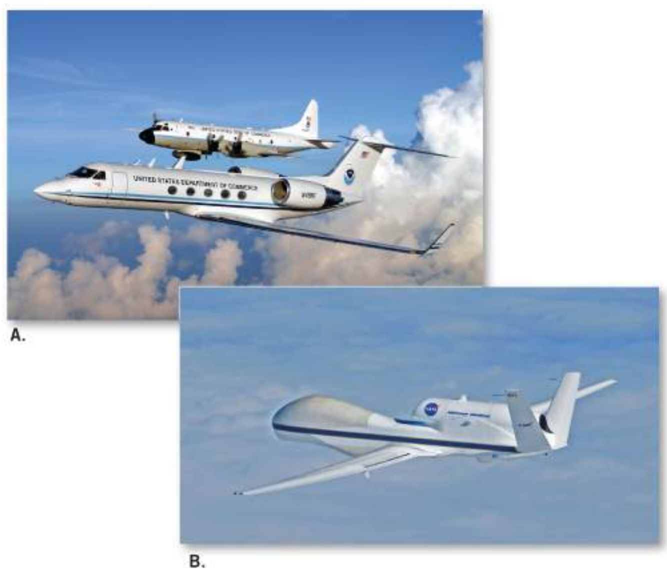
This satellite also contains a microwave radiometer, which detects the total precipitation in a vertical column. Information from both instruments can be used to identify massive cumulonimbus clouds called **hot towers**, sometimes more than 12 kilometers (7 miles) high, that develop within an eyewall before a hurricane intensifies.

Aircraft Reconnaissance

Estimating hurricane intensity is difficult because direct *surface* observations below the eye wall are rarely available due to cloud cover. Therefore, surface winds in the most intense part of the storm must be estimated. Usually, the most effective way to obtain such estimates is with *reconnaissance aircraft*, popularly called *hurricane hunters* (Figure 11.20A). When a hurricane is within range, specially instrumented aircraft can fly directly into a threatening storm to accurately measure details of its position and current state of development. Data transmission is made directly from the aircraft in the midst of a storm to the forecast center, where the input is applied to a forecast model.

Figure 11.20 **Aircraft reconnaissance**

A. In the Atlantic basin, most operational hurricane reconnaissance is carried out by the U.S. Air Force Reconnaissance Squadron, using planes like the one in the background of this image. Pilots fly through the hurricane to its center, measuring all basic weather elements as well as providing an accurate location of the eye. The National Oceanic and Atmospheric Administration uses small, specially equipped jets (foreground) on research missions to aid scientists in better understanding these storms. **B.** The *Global Hawk,* a drone measuring 13.2 meters (44 feet), can climb to heights of 19.5 kilometers (65,000 feet) and remain airborne for up to 30 hours.

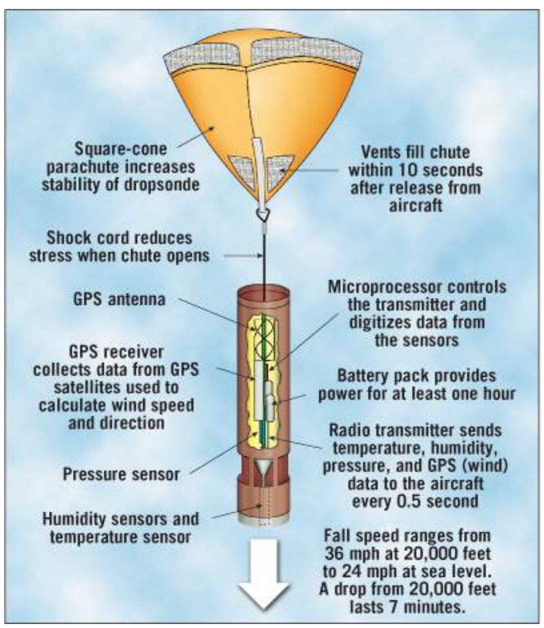


Dropsonde

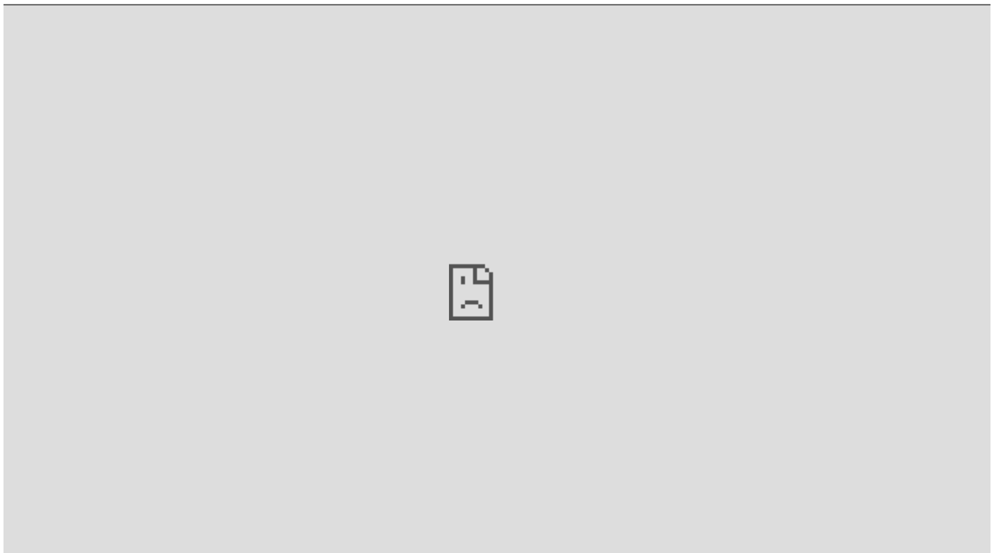
Another important development in aircraft reconnaissance is an instrument called a *Global Positioning System (GPS) dropwindsonde*, often abbreviated to **dropsonde**. After being released from the aircraft, this instrument package drifts downward through the storm (Figure 11.21). During the descent, it continuously transmits data on temperature, humidity, air pressure, wind speed, and wind direction. The development of this technology allows for accurate measurement of the winds in a hurricane—from flight level all the way to the surface.

Figure 11.21 Dropsonde

This cylindrical instrument package, roughly 7 centimeters (2.75 inches) in diameter and 40 centimeters (16 inches) long, weighs about 0.4 kilograms (0.86 pounds). The instrument package is released from an aircraft and falls through the storm via a parachute, making and transmitting measurements of temperature, pressure, winds, and humidity every half-second.



Watch **Video: Improving Hurricane Prediction**



> Reconnaissance aircraft are used to directly measure conditions inside a hurricane using dropsondes.

It is worth noting, however, that data from dropsondes are limited because they are not taken continuously or throughout the storm. Rather, these instrument packages provide sample "snapshots" of small parts of the hurricane. Despite this drawback, dropsondes have improved our understanding of hurricanes tremendously. The data accumulated from hundreds of dropsondes showed that the speed of surface winds below the eyewall averaged about 90 percent of the flight-level winds. Based on this understanding, the National Hurricane Center now uses the 90 percent figure to estimate a hurricane's maximum surface winds from flight-level observations.

Drone Aircraft

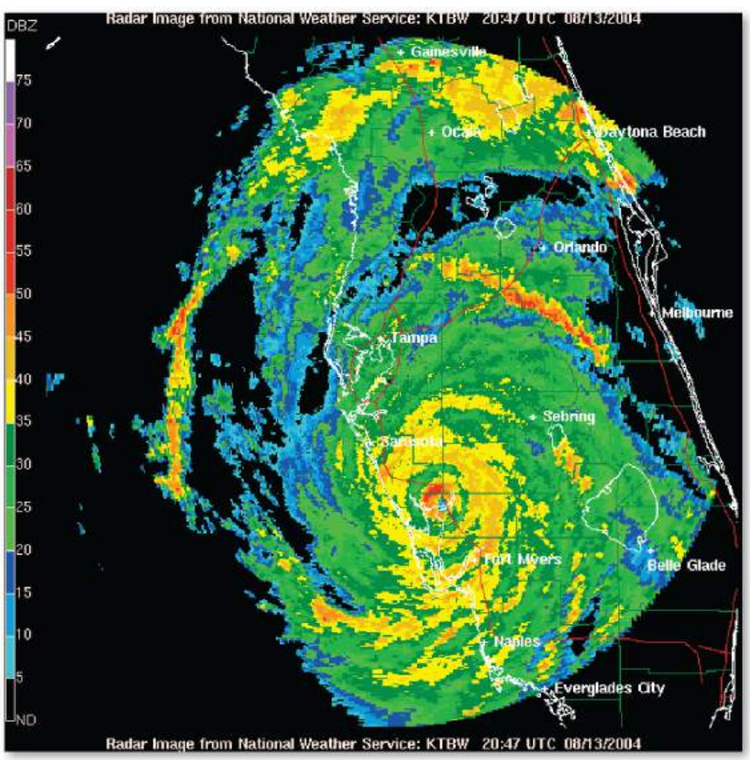
A new form of aircraft reconnaissance is in the developmental stage and makes use of an unstaffed drone aircraft (Figure 11.20B). The *Hurricane and Severe Storm Sentinel* (*HS3*), a 5-year program begun by NASA in 2012, is intended to enhance understanding of processes involved in hurricane intensity changes in the Atlantic basin.

Radar

Ground-based radar is a third basic tool in the observation and study of hurricanes (Figure 11.22). When hurricanes approach a coast, they are monitored by land-based Doppler weather radar (discussed in greater detail in Chapter 10). Doppler radar provides detailed information on hurricane wind fields, rainfall intensity, and storm movement. As a result, local National Weather Service personnel are able to provide short-term warnings for floods, tornadoes, and high winds for specific areas. A limitation of radar is that it cannot “see” farther than about 320 kilometers (200 miles) from the coast, and hurricane watches and warnings must be issued long before a storm comes into range.

Figure 11.22 Coastal Doppler radar

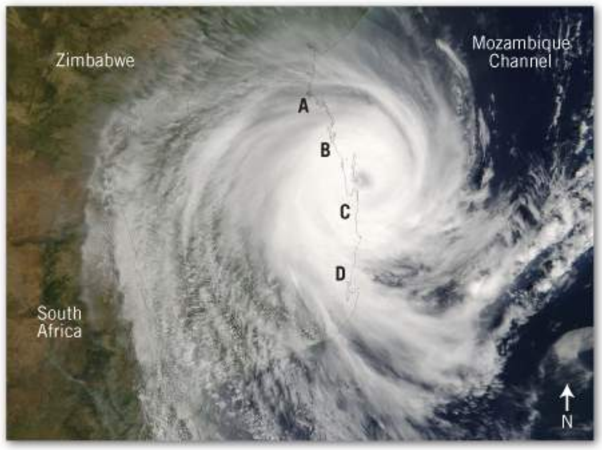
Doppler radar image of Hurricane Charley over Charlotte Harbor, Florida, just after landfall on August 13, 2004. The range of coastal radar is about 320 kilometers (200 miles).



Rapidly intensifying storms can catch vulnerable coastal areas by surprise. For example, in 2007 Hurricane Humberto struck near Port Arthur, Texas, after unexpectedly strengthening from a tropical depression to a hurricane in less than 19 hours. To improve short-term hurricane warnings, a technique known as VORTRAC (*V*ortex *O*bjective *R*adar *Tr*acking *a*nd *C*irculation) captures sudden intensity changes during the critical time when the storm is nearing land. VORTRAC employs the Doppler radar network along the Gulf and Atlantic coastline from Texas to Maine. Each unit can measure winds blowing toward or away from it. By combing data for multiple radar units, forecasters can estimate a hurricane's rotational winds and central pressure.

Eye on the Atmosphere 11.2

This satellite image shows Tropical Cyclone Favio as it came ashore along the coast of Mozambique, Africa, on February 22, 2007. This powerful storm was moving from east to west, with portions of the cyclone having sustaining winds of 203 kilometers (126 miles) per hour as it made landfall.



Apply What You Know

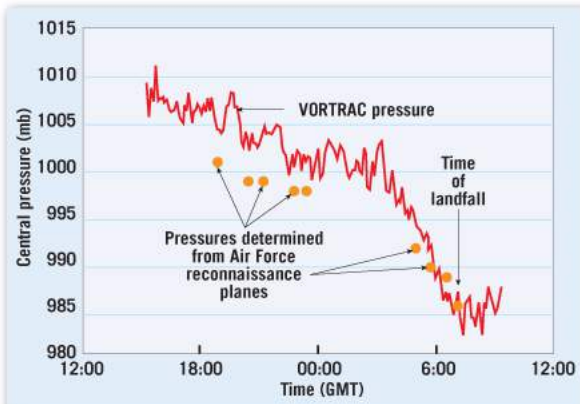
1. Identify the eye and eyewall of the storm.
2. Based on wind speed, classify the storm using the Saffir–Simpson scale.
3. Which one of the lettered sites should experience the strongest storm surge? Explain.

VORTRAC can also be used to estimate the barometric pressure in the eye of the hurricane, which is a reliable indicator of its strength (Figure 11.23). Each radar can sample conditions to a distance of 190 kilometers

(120 miles), allowing forecasters using VORTRAC to update the status of a storm about every 6 minutes.

Figure 11.23 VORTRAC

VORTRAC captured the storm's rapid intensification, indicating that the pressure began falling quickly near the end of a 4-hour span when no aircraft data were available.



Data Buoys

Data buoys provide a fourth method of gathering data for the study of hurricanes (see Figure 12.4). These remote, floating instrument packages are positioned in fixed locations along the Gulf and Atlantic coasts of the United States. Examination of the weather maps in Figure 11.4 reveals data buoy information plotted at several offshore stations. Since the early 1970s, data provided by these units have become a dependable and routine part of daily weather analysis as well as an important element of the hurricane warning system. The buoys provide the only means of making nearly continuous direct measurements of surface conditions over large ocean areas.

Concept Checks 11.4

- Why is estimating the surface wind speeds of a hurricane difficult?
- Explain the role that each of the following plays in tracking and monitoring hurricanes: satellite, reconnaissance aircraft, and radar.

11.5 Forecasting Hurricanes

LO 5 Describe hurricane forecasting methods and contrast the terms *hurricane watch* and *hurricane warning*.

Before a hurricane makes landfall, locations only a few hundred kilometers from it—just a day's striking distance away—may experience clear skies and virtually no wind. As a result, before the age of weather satellites it was difficult to identify and track impending storms. The worst natural disaster in U.S. history was caused by a hurricane that struck an unprepared Galveston, Texas, on September 8, 1900. The strength of the storm, combined with the lack of adequate warning, caught the population by surprise and claimed the lives of 6000 people in the city and at least 2000 more elsewhere (Figure 11.24).*

Figure 11.24 Aftermath of the Galveston hurricane of 1900

Entire blocks were swept clean, and mountains of debris accumulated around the few remaining buildings.

In the United States, early-warning systems have greatly reduced the number of deaths caused by hurricanes. Simultaneously, however, property damage amounts have risen astronomically. The primary reason for this latter trend is rapid population growth and accompanying development in coastal areas.

Hurricane Forecasting Tools

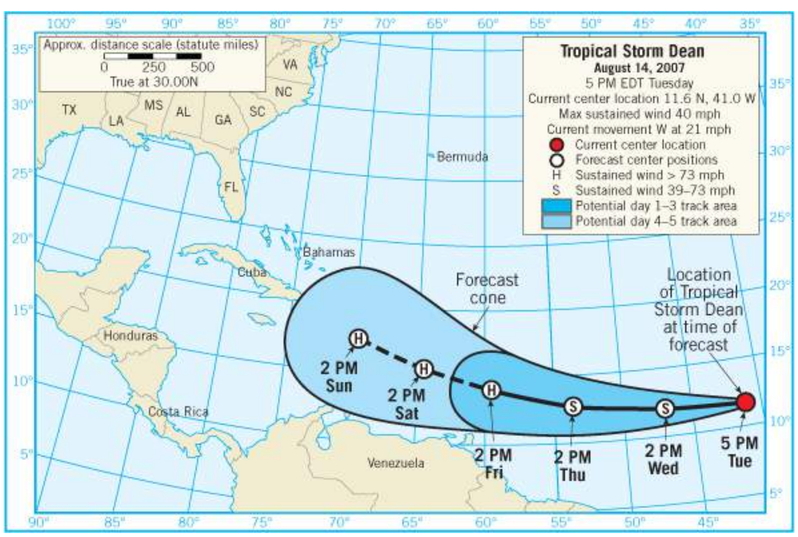
Hurricane forecasts are a basic part of any warning system. We certainly want to know where a storm is headed, and forecasters also want to know the strength of the winds, probable rainfall amounts, and likely size of the storm surge.

Track Forecasts

A **track forecast cone** provides the most basic information about a hurricane because accurate prediction of other storm characteristics is of little value without some certainty of where the hurricane is likely to make landfall (Figure 11.25). On a track forecast cone, the current location of a hurricane is shown by an orange dot. The predicted track gets more uncertain the further into the future a prediction is needed, so the forecast cone gets wider. The width indicates the uncertainty of the storm track, not the size of the storm. Changes in storm intensity, steering winds, and other factors can mean that the storm track can vary by hundreds of kilometers.

Figure 11.25 Five-day track forecast cone for Tropical Storm Dean

When the National Hurricane Center issues a hurricane track forecast, it is termed a *forecast cone*. The cone represents the probable track of the center of the storm and is formed by enclosing the area swept out by a set of circles along the forecast track. The size of each circle gets larger with time.



Accurate track forecasts are important because they can lead to timely evacuations from the surge zone, where the greatest numbers of deaths usually occur. Fortunately, track forecasts have been steadily improving. Modern 5-day track forecasts are as accurate as the 3-day forecasts of the beginning of this century. Much of the progress is due to improved computer models and a dramatic increase in the quantity of satellite data from over the oceans. Despite improvements in accuracy, however, forecast uncertainty still requires that hurricane warnings be issued for relatively large coastal areas.

Forecasting Other Characteristics

Forecasts for rainfall totals and inland flooding have greatly improved with the launch of the GPM satellite. Coastal radar also allows accurate forecasting of rainfall, wind speeds, and possible tornado locations. Storm surge is currently forecast by the National Hurricane Center's SLOSH (Sea, Lake, and Overland Surges from Hurricanes) computer model. Louisiana State University is also developing high-resolution models to predict storm surge and inland flooding.

Hurricane Watches and Warnings

Using input from the observational tools in conjunction with sophisticated computer models, meteorologists attempt to forecast a hurricane's movements and intensity. The goal is to issue timely watches and warnings.

A **hurricane watch** is an announcement that hurricane conditions are *possible* in a specified coastal area. To give residents adequate time to prepare and evacuate, a hurricane watch is issued 48 hours in advance of the anticipated onset of tropical storm–force winds. By contrast, a **hurricane warning** is issued 36 hours in advance and indicates that hurricane conditions are *expected* somewhere within a specified coastal area. A hurricane warning can remain in effect when dangerously high water or a combination of dangerously high water and exceptionally high waves continues, even though winds may be less than hurricane force.

Severe & Hazardous Weather 11.2

Super Typhoon Haiyan

The chapter-opening image shows Super Typhoon Haiyan as it moved across the central Philippines on November 8, 2013. Shortly before the storm struck, the Joint Typhoon Warning Center (JTWC) in Hawaii estimated the winds to be 315 kilometers (195 miles) per hour, making it a category 5 storm on the Saffir–Simpson scale (Figure 11.A). The JTWC, a U.S. Navy and Air Force task force, monitors storms in the Pacific and Indian Oceans. If the JTWC estimate was accurate, Haiyan was the strongest storm on record ever to make landfall.

Figure 11.A Haiyan's path

The map shows the path of this very strong storm. Numbers indicate the intensity of the storm on the Saffir–Simpson scale. After striking the central Philippines, Haiyan made landfall again in Vietnam.

> Haiyan was the strongest storm on record ever to make landfall.

Whereas Haiyan's sustained winds were estimated to be 315 kilometers (195 miles) per hour, gusts may have reached 370 kilometers (230 miles) per hour. Imagine billions of raindrops and flying debris moving at that speed!

It is rare that a storm happens to reach peak intensity as it makes landfall along a densely populated coast, but such was the case with Haiyan—the deadliest Philippine typhoon on record. Officially the death toll reached 6300, but the loss of life was undoubtedly much higher, as thousands remained unaccounted for. In addition, 2 million people lost their homes, and millions more were displaced.

Although winds were extreme, Haiyan's storm surge was the major cause of life and property losses. At Tacloban, perhaps the hardest-hit city, the wall of water is estimated to have been as high as 7.5 meters (nearly 25 feet). Because much of the city is less than 5 meters (16 feet) above sea level, the result was catastrophic. In addition to the fierce winds and powerful storm surge, Haiyan produced copious rainfall in the central Philippines. Dangerous flooding and mudflows in this mountainous country were widespread.

Weather Safety

The National Hurricane Center recommends the following during a hurricane:

- Stay away from low-lying areas.
- Stay indoors.
- Evacuate immediately if directed to by emergency officials.

Apply What You Know

1. What is a super typhoon? Why is there some uncertainty about the strength of Haiyan's winds?
2. Describe the types of hurricane destruction that Haiyan caused in the Philippines.

Two factors are especially important in the watch-and-warning decision process. First, adequate lead time must be provided to protect life and, to a lesser degree, property. Second, forecasters must attempt to keep *overwarning* at a minimum, because people may refuse to leave their homes and businesses if they have experienced false alarms in the past. This, however, can be a difficult task. Clearly, the decision to issue a warning involves striking a delicate balance between the need to protect the public on the one hand and the desire to minimize the degree of overwarning on the other.

Concept Checks 11.5

- What was the worst natural disaster in U.S. history? Why is such an event unlikely to occur in the United States again?
- Distinguish between a *hurricane watch* and a *hurricane warning*.
- What is a track forecast? Why are such forecasts important?

* For a fascinating account of the Galveston storm, read Isaac's Storm by Erik Larson (New York: Crown Publishers, 1999).

Concepts in Review

11.1 Profile of a Hurricane

LO 1 Sketch and describe the basic structure and circulation of a hurricane.

Key Terms

hurricane

sustained winds

eye

eye wall

rain band

- Hurricanes are intense centers of low pressure that form over warm oceans in the tropics and subtropics. To be designated as a hurricane, the storm's sustained winds must equal or exceed 119 kilometers (74 miles) per hour.
- Most hurricanes form between latitudes 5° and 30° over all tropical oceans except the South Atlantic and eastern South Pacific. In the northwestern Pacific, hurricanes are called *typhoons*, and in the southwestern Pacific and Indian Oceans, they are termed *cyclones*.
- A steep pressure gradient generates the rapid, inward-spiraling winds of a hurricane. As the warm, moist air approaches the core of the storm, it turns upward, ascends in a ring of cumulonimbus towers, and forms a doughnut-shaped wall called the eye wall. Concentric rings of thunderstorm-producing clouds called rain bands surround the eye wall.

11.2 Hurricane Formation and Decay

LO 2 Discuss the conditions that promote hurricane formation and the factors that cause hurricanes to dissipate.

Key Terms

tropical disturbance

easterly wave (tropical wave)

tropical depression

tropical storm

- A hurricane is a heat engine fueled by the latent heat liberated when huge quantities of water vapor condense. They develop from a cluster of thunderstorms most often in late summer, when ocean waters have reached temperatures of 27°C (80°F) or higher and provide the necessary heat and moisture to the air above.
- Tropical disturbances that produce many of the strongest hurricanes often begin as large undulations in the trade winds, called easterly waves.
- When a cyclone's strongest winds do not exceed 63 kilometers per hour, it is called a tropical depression. When winds are between 63 and 119 kilometers per hour, the cyclone is termed a tropical storm.
- Hurricanes diminish in intensity when they (1) move over cool ocean waters that cannot supply warm, moist tropical air; (2) move onto land; or (3) reach a location where large-scale flow aloft is unfavorable.

11.3 Hurricane Destruction

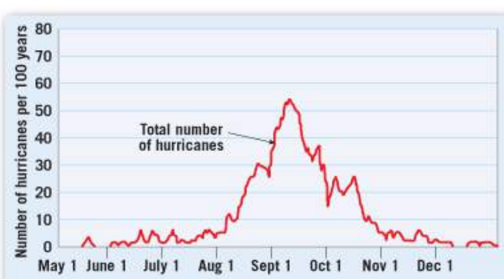
LO 3 Explain how hurricane intensity is classified and summarize the three broad categories of hurricane destruction.

Key Terms

Saffir–Simpson scale

storm surge

- Although damages caused by a hurricane depend on several factors, the most significant factor is the strength of the storm.
- The Saffir–Simpson scale ranks the relative intensities of hurricanes. A 5 on the scale represents the strongest storm possible, and a 1 is the least severe.
- Along the coast, storm surge is responsible for the greatest loss of life and property damage. This wall of water is created by the strong onshore winds.
- Destruction by hurricane-force winds can cover a broad area. Sometimes wind damage results from tornadoes spawned by the hurricane.
- Torrential rains and flooding are often associated with hurricanes. Long after a storm has come ashore and lost its hurricane-force winds, it may still produce copious rain.



11.4 Tracking and Monitoring Hurricanes

LO 4 Summarize the methods used to track and monitor hurricanes.

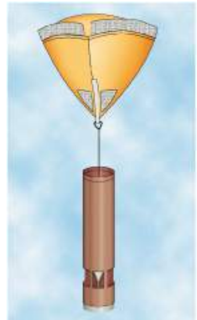
Key Terms

radar scatterometer

hot tower

dropsonde

- North Atlantic hurricanes develop in the trade winds, which generally move these storms from east to west.
- Because the regions that spawn hurricanes consist of enormous areas of open oceans, meteorological data from these vast regions are provided primarily by satellites, which can be used to track these storms, predict rapid intensification, and map rainfall.
- Scatterometers, a type of radar aboard ocean-monitoring satellites, estimate surface winds.
- Other important sources of hurricane information are aircraft reconnaissance, radar, and data buoys. Dropsondes are instrument packages released by reconnaissance airplanes. During descent, the dropsonde continuously transmits meteorological data. Doppler radar is used to monitor storm intensity once a hurricane nears the coastline.



11.5 Forecasting Hurricanes

LO 5 Describe hurricane forecasting methods and contrast the terms *hurricane watch* and *hurricane warning*.

Key Terms

track forecast cone

hurricane watch

hurricane warning

- Track forecasts identify potential areas where hurricane landfall may occur so that evacuations can occur in a timely manner.
- Hurricane watches and warnings alert coastal residents to possible or expected hurricane conditions. Two important factors in the watch-and-warning decision process are providing adequate lead time and attempting to keep overwarning to a minimum.

Exercises and Online Activities

Mastering Meteorology™

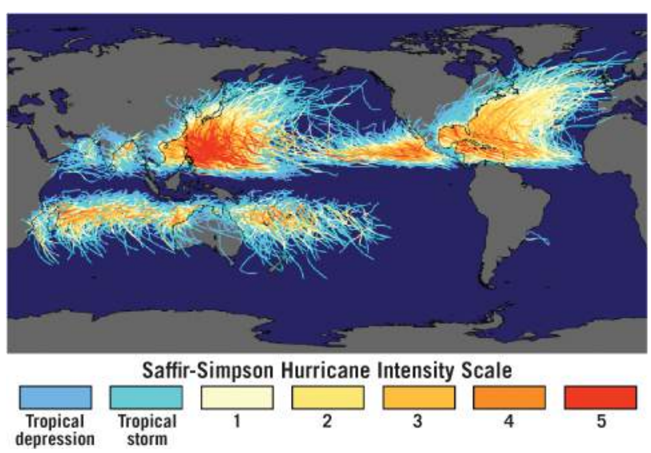
For instructor-assigned homework, test prep resources, and other learning materials, visit **Mastering Meteorology.**

Review Questions

1. Which region of the globe has the highest incidence of strong tropical storms? When are they most likely to occur?
2. Sketch and describe the three basic structures of a hurricane. Briefly describe the main circulation pattern associated with a hurricane.
3. List the three conditions necessary for hurricane formation.
4. Describe tropical disturbances, and explain why they form in association with easterly waves.
5. Is a tropical cyclone an area of high or a low pressure?
6. Describe the characteristics of a tropical storm.
7. Where are the winds and precipitation most intense in a hurricane?
8. What cloud type is dominant in hurricanes?
9. Describe how air pressure, wind speed, and rainfall intensity change as you move from the perimeter to the eye of an average hurricane.
10. Describe the three main conditions that result in hurricane decay.
11. What is the highest hurricane category on the Saffir-Simpson Scale? How often do hurricanes of this strength strike the United States?
12. Explain why the right side (relative to its forward movement) of a hurricane that forms in the Northern Hemisphere is the most destructive.
13. Define *storm surge*.
14. Describe the typical path of a strong North Atlantic hurricane.
15. List four tools used to track and monitor hurricanes.
16. What important role do satellites play in monitoring hurricanes?
17. Describe a track forecast, and explain its cone shape.

Give It Some Thought

1. **1.** Why might people in some parts of the world welcome the arrival of hurricane season?
2. **2.** Hurricanes are sometimes referred to as "heat engines." What "fuel" provides the energy for these high-powered engines?
3. **3.** Although observational tools and hurricane forecasts continue to improve, the potential for loss of property due to hurricanes is likely growing. Suggest a reason for this apparent contradiction.
4. **4.** The accompanying world map shows the tracks and intensities of nearly 150 years of tropical cyclones. It is based on all storm tracks available from the National Hurricane Center and the Joint Typhoon Warning Center.
   - **a.** What area has experienced the greatest number of category 4 and 5 storms?
   - **b.** Why do hurricanes *not* form in the very heart of the tropics, astride the equator?
   - **c.** Explain the absence of storms in the South Atlantic and eastern South Pacific.



5. **5.** A television meteorologist is able to inform viewers about the intensity of an approaching hurricane. However, the

meteorologist can report the intensity of a tornado only *after* it has occurred. Why is this true?

6. Assume that it is late September 2020, and Hurricane Hanna, a category 5 storm, is projected to follow the path shown on the accompanying map. Answer the following questions.

a. Name the stages of development that Hanna must have gone through to become a hurricane. At what point did it receive its name?

b. Should the city of Houston expect to experience Hanna's fastest winds and greatest storm surge? Explain why or why not.

c. What is the greatest threat to life and property if this storm approaches the Dallas–Fort Worth area?

By the Numbers

Questions 1–4 refer to the weather map of Hurricane Sandy in Figure 11.4.

1. Answer the following questions about the movement of the storm.
   a. How far did the center of the Hurricane Sandy move during the 24-hour period from October 26 to October 27?
   b. At what rate, in miles per hour, did the storm move during this 24-hour span?
2. The midlatitude cyclone shown in Figure 9.20 has an east–west diameter of approximately 1200 miles. Measure the diameter (north–south) of Hurricane Sandy using the 1000-millibar isobar to represent the outer edge of the storm. How does this figure compare to the midlatitude cyclone? (Note: Hurricane Sandy was an unusually large hurricane.)
3. Determine the pressure gradient for Hurricane Sandy on October 29. Measure from the 1008-millibar isobar at the top (north) to the center of the storm, which had a pressure of 952 millibars. Express your answer in millibars per 100 miles.
4. The weather map in Figure 9.20 shows a well-developed midlatitude cyclone. Calculate the pressure gradient of this storm from the 1008-millibar isobar in western Wyoming to the center of the low. Assume that the pressure at the center of the storm is 986 millibars and the distance is 600 miles. Express your answer in millibars per 100 miles. How does this answer compare to your answer to Question 3?
5. Hurricane Rita was a major storm that struck the Gulf coast in late September 2005, less than a month after Hurricane Katrina. The accompanying graph shows changes in air pressure and wind

speed from the storm's beginning (as an unnamed tropical disturbance north of the Dominican Republic on September 18) until its last remnants faded away in Illinois on September 26. Use the graph to answer these questions.

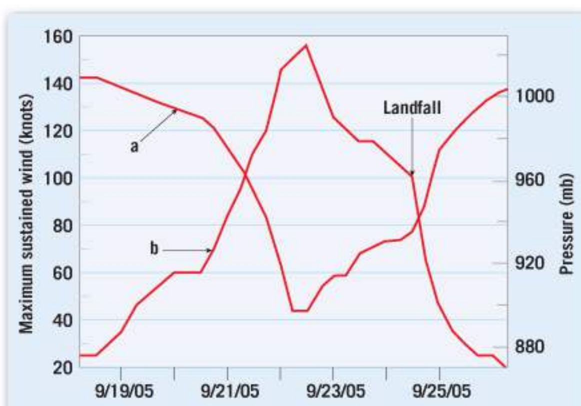
a. Which line represents air pressure, and which line represents wind speed? How did you determine your answer?

b. What was the storm's maximum wind speed, in knots? Next, convert your answer to kilometers per hour by multiplying by 1.85.

c. What was the lowest pressure attained by Hurricane Rita?

d. Using wind speed as your guide, what was the highest category reached on the Saffir–Simpson scale? On what day was this status reached?

e. When landfall occurred, what was the category of Hurricane Rita?



Beyond the Textbook

Hurricane Katrina

Hurricane Katrina was the costliest hurricane in United States history, with damages totaling $108 billion. It was also one of the deadliest, with 1833 deaths. More than 1 million people were displaced in the Gulf coast region.

1. Hurricane Katrina's Track

Go to the National Weather Service Katrina Graphics Archive at http://www.nhc.noaa.gov/archive/2005/KATRINA_graphics.shtml. Click on "3-day Cone/Warnings" and click the two forward arrows under "Loop Image" to analyze Karina's track. If necessary, you can stop the animation, adjust the speed, and advance the animation one frame at a time.

1. Describe the path of Hurricane Katrina. Was the path typical or erratic?
2. When was a hurricane watch issued for the Gulf coast? When was this changed to a hurricane warning?
3. On what date did the eye (center) of Hurricane Katrina make landfall?
4. Which states experienced the strongest winds? Was this area located mainly to the east or west of where Katrina made landfall?

2. Hurricane Katrina's Damages

Find a map online and locate New Orleans, Louisiana, and Gulfport, Mississippi. Most loss of life occurred in New Orleans, which has an average elevation of about 1–2 feet below sea level, with some areas as low as 2 meters (7 feet) below sea level. Levies and floodwalls holding back the waters from Mississippi River and Lake Pontchartrain broke at several locations because of unusually heavy rainfall.

1. Do an Internet search for "Hurricane Katrina New Orleans damage pictures" and describe the damage in New Orleans.
2. Do an Internet search for "Hurricane Katrina Gulfport-Biloxi, Mississippi damage pictures." In general, describe how the damage in the area around Gulfport and Biloxi was different from that of New Orleans.
3. What phenomena caused the differences you described in Question 2?

Chapter 12 Weather Analysis and Forecasting

While a January 2016 snowstorm emptied vehicle traffic from New York City's Times Square, this woman built a snowman.

Focus on Concepts

Each statement represents the primary learning objective for the corresponding major heading within the chapter. After you complete the chapter, you should be able to:

1. List and describe the major steps used to generate a weather forecast (12.1).
2. Describe the various tools used to acquire weather data (12.2).
3. Interpret what a particular pattern in the flow aloft indicates about surface weather (12.3).
4. Explain the basis of numerical weather prediction (12.4).
5. Distinguish among the various traditional methods of weather forecasting (12.5).
6. Discuss the advantages and disadvantages of infrared, visible, and water-vapor imagery generated by weather satellites (12.6).
7. Compare and contrast qualitative and quantitative weather forecasts. Differentiate between weather forecasts and 30- and 90-day outlooks (12.7).
8. Describe how AWIPS and thermodynamic diagrams are used by local Weather Forecast Offices. List strategies for forecasting temperature and precipitation (12.8).
9. Explain why the percentage of accurate forecasts is not always a good measure of forecast skill (12.9).

The desire for reliable weather predictions ranges from NASA's need to evaluate conditions leading up to a satellite launch to families wondering if the upcoming weekend weather will be suitable for a beach outing. Such diverse industries as airlines and fruit growers depend heavily on accurate weather forecasts. In addition, the designs of buildings, oil platforms, and industrial facilities rely on a sound knowledge of the atmosphere in its most extreme forms, including thunderstorms, tornadoes, and hurricanes.

12.1 The Weather Business: A Brief Overview

LO 1 List and describe the major steps used to generate a weather forecast.

The U.S. government agency responsible for gathering and disseminating weather-related information is the **National Weather Service (NWS)**, a branch of the *National Oceanic and Atmospheric Administration* (*NOAA*) (Figure 12.1). Perhaps the most important services provided by the NWS are forecasts and warnings of hazardous weather, including thunderstorms, floods, hurricanes, tornadoes, winter weather, and extreme heat (Figure 12.2). According to the *Federal Emergency Management Agency* (*FEMA*), 80 percent of all declared emergencies are weather related. As a result, the NWS is under continual pressure to provide more accurate and longer-range forecasts.

Figure 12.1 Partial organizational chart for National Oceanic and Atmospheric Administration (NOAA)

This chart shows the relationship between the parent organization (NOAA), the National Weather Service (NWS), and the NWS branches responsible for collecting and analyzing weather data, as well as producing and disseminating weather forecasts.

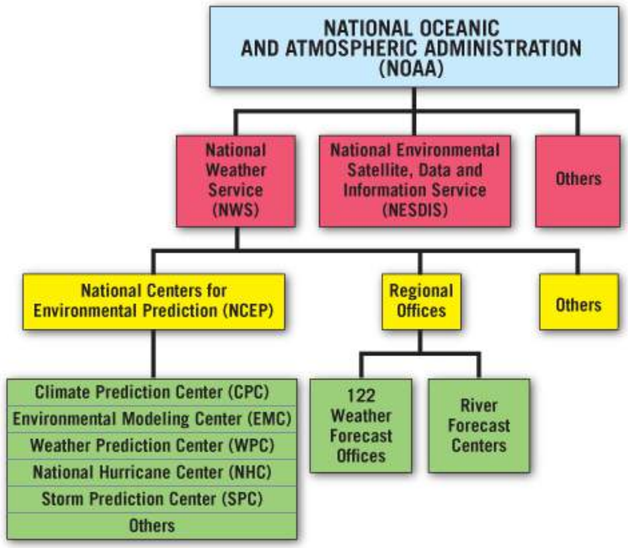


Figure 12.2 Highway washed out by Hurricane Matthew, Flagler Beach, Florida, October 2016.

Producing a Weather Forecast

What is a weather forecast? Simply, a **weather forecast** is a scientific estimate of the weather conditions at some future time. Forecasts are usually expressed in terms of the most significant weather variables, including temperature, cloudiness, humidity, precipitation, wind speed, and wind direction.

The first phase of forecasting involves the complicated and detailed process of *collecting* and *assimilating* weather data on a global scale. In the United States, this formidable task is performed by a division of the NWS called the **National Centers for Environmental Prediction (NCEP)**, located in College Park, Maryland. The NCEP is also responsible for using these data to make predictions about the future state of the atmosphere. In Canada, the **Canadian Meteorological Centre** performs these tasks.

When billions of pieces of observational data are collected, meteorologists fine-tune the data by correcting as many errors and omissions as possible. This important step ensures the most accurate assessment possible of the current atmospheric conditions. It also involves "smoothing" the data to make it compatible with computer models that meteorologists use to make forecasts. Simultaneously, the data are displayed on surface weather maps and upper-level charts that forecasters can easily comprehend. Once weather maps are refined, meteorologists analyze them and ask questions such as, "Where are the fronts and major weather systems located, and how have they changed over time?" This phase of forecasting is called *weather analysis*.

Next, the NCEP, through its various branches, begins the *predictive*, or *forecast*, *phase*. Modern weather forecasting employs supercomputers programmed to solve basic mathematical equations that describe atmospheric behavior. Using current weather data, these computer models attempt to predict the atmospheric conditions at the end of the forecast period—for example, 12 hours into the future. As part of the forecasting process, the NCEP regularly prepares surface forecast maps and various other forecast products on national as well as global scales. These materials are supplied to the 122 local **Weather Forecast Offices (WFO)**, where they are used to produce local and regional weather forecasts. Experienced forecasters at each WFO tweak the computer-generated forecasts by using traditional forecasting techniques and knowledge of their particular forecast area in an effort to increase accuracy.

> Meteorologists at Weather Forecast Offices create local forecasts that are shared with the public.

The final phase in the weather business is the dissemination of a wide variety of forecasts. Each Weather Forecast Office issues regional and local forecasts, aviation forecasts, and weather and flood warnings covering its forecast area. Further, all observational data and products (maps, charts, and forecasts) produced by the NCEP are available, mainly via the Internet, to the general public, government agencies responsible for public safety, and private forecasting services such as The Weather Channel, AccuWeather, and Weather Underground.

The demand for highly visual forecasts containing computer-generated graphics has increased proportionately with the use of personal computers and smartphones. Most weather animations that appear on most local newscasts are produced by the private sector. Private-sector companies also customize forecast products to create specialized weather reports tailored for specific audiences. In a farming community, for example, the weather reports might include freeze warnings, while winter forecasts in Denver, Colorado, include the snow conditions at area ski resorts.

Despite the valuable role that the private sector plays in generating and disseminating weather-related information to the public, the NWS is the *official* voice in the United States for issuing warnings during hazardous and life-threatening weather situations. Two major weather centers operated by the NWS serve critical functions in this regard. The Storm Prediction Center (SPC) in Norman, Oklahoma, maintains a constant vigil for severe weather, including thunderstorms and tornadoes, as well as heavy snowfall. Hurricane watches and warnings for the Atlantic, Caribbean, Gulf of Mexico, and eastern Pacific are issued by the National Hurricane Center (NHC) located in Miami, Florida.

Who's Who in Weather Forecasting?

The American Meteorological Society defines a **meteorologist** as a person with specialized education, usually a bachelor's degree or higher from a college or university, who uses scientific principles to explain, observe, study, or forecast atmospheric phenomena. The broader term *atmospheric scientist* is sometimes used synonymously with *meteorologist* to describe someone who studies some aspect of Earth's atmosphere. Meteorologists perform various duties such as weather forecasting, atmospheric research, teaching, broadcasting, and providing specialized weather-related products to clients through private-sector companies.

Weather forecasting has always been the primary task of meteorologists. Forecasters are employed by a variety of organizations, including:

- The NWS, a primary employer of meteorologists in the United States
- The aviation industry, which hires meteorologists to provide pilots with information on weather conditions—such as possible turbulence during take-offs, landings, and during flights
- The military, particularly the Air Force and Navy, which uses meteorologists to make weather forecasts for missions around the world
- The National Aeronautical and Space Administration (NASA), which employs forecasters to monitor weather conditions for satellite launches
- Private companies, the fastest-growing area for employing meteorologists
- The National Center for Atmospheric Research (NCAR) in Boulder, Colorado, which employs meteorologists to do research

Today, television stations employ more than 2000 meteorologists—both those behind the scenes where forecasts are prepared, as well as broadcast meteorologists who present forecasts and related weather information to viewers. What separates *broadcast meteorologists* from other meteorologists is their ability to describe complex meteorological phenomena to the public in a way that is easily understood (Figure 12.3). TV and radio stations that do not employ their own meteorologists usually purchase local weather forecasts from private companies. People not trained as meteorologists, often referred to as *weathercasters*, disseminate these forecasts to the public.

Figure 12.3 The duties of a broadcast meteorologist include describing complex meteorological phenomena to the general public in a way that is easily understood.

Concept Checks 12.1

- What role does the Storm Prediction Center (SPC) serve?
- List the major steps involved in providing weather forecasts.
- How do broadcast meteorologists differ from meteorologists who prepare weather forecasts?

12.2 Acquiring Weather Data

LO 2 Describe the various tools used to acquire weather data.

Before weather can be predicted, forecasters must have an accurate picture of current atmospheric conditions. This involves collecting, transmitting, and compiling billions of pieces of observational data. Because the atmosphere is ever-changing, these tasks must be accomplished quickly.

On a global scale, the **World Meteorological Organization (WMO)**, a United Nations agency, is responsible for the international exchange of weather data. This task requires that data from more than 185 participating nations and 6 territories around the globe be collected simultaneously, standardized, and transmitted to the participating countries.

Surface Observations

Worldwide, about 11,000 observation stations on land, 4000 ships at sea, and 1200 data buoys (Figure 12.4) report atmospheric conditions. These data are rapidly sent around the globe, using a communications system dedicated to the distribution of weather information.

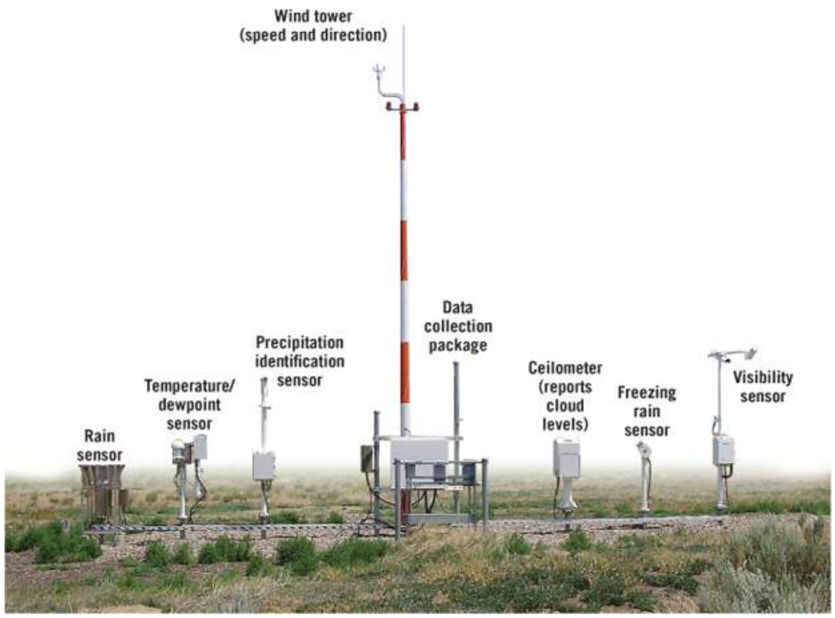
Figure 12.4 **Data buoy used to record atmospheric conditions over a section of the global ocean**

The data this buoy collects are transmitted via satellite to a land-based station.

In the United States, employees of the 122 Weather Forecast Offices are responsible for gathering and transmitting local weather information to a central database. In addition, the NWS operates more than 900 **Automated Surface Observing Systems (ASOS)**. These modern automated systems provide weather observations such as temperature, dew point, wind speed and direction, visibility, and cloud cover, and they can also determine precipitation type and amount (Figure 12.5). The Federal Aviation Administration (FAA), in cooperation with the NWS, also operates automated observation stations at many airports. Automation assists, or in some cases replaces, human observers because it can provide information from remote areas. However, some research has shown that human observers are more reliable at determining certain weather elements, such as cloud cover and sky conditions.

Figure 12.5 Automated Surface Observing System (ASOS)

Automated observing systems are equipped with a variety of instruments designed to sample the sky for cloud coverage; take temperature and dew-point measurements; determine wind speed and direction; and even detect present weather—such as whether it is raining or snowing.



Automated Surface Observing Systems (ASOS) report weather data automatically.

Observations Aloft

Because weather systems are three-dimensional, upper-air observations are essential for producing reliable forecasts. **Radiosondes** are the primary tool for gathering weather data aloft. These lightweight instrument packages, which contain sensors to measure temperature, humidity, and pressure, are carried aloft by weather balloons (see Figure 1.21). These data are transmitted via radio to the local observation station that launched it, usually a Weather Forecast Office. Recall that radiosonde data, known as an **atmospheric sounding** or simply a **sounding**, is used to assess the stability of the air and to generate upper-air weather maps.

> Radiosonde data, termed a *sounding*, are used to assess the stability of the air and to generate upper-level maps.

Worldwide, about 1300 radiosondes are launched twice daily, so they are aloft at approximately 0000 and 1200 Coordinated Universal Time (UTC), also called Greenwich Mean Time (GMT). Ships at sea also launch some radiosondes, and some airplanes drop a similar type of instrument that floats to the ground. In addition, about 4000 aircraft report on atmospheric conditions aloft—mainly temperature and airflow data—during flight.

Despite the advances in weather data collection, two difficulties remain. First, the network of weather observation stations does not provide consistent coverage around the globe—particularly over the oceans and in remote areas. Second, observations may have inaccuracies due to instrument and/or transmission error.

You might have wondered . . .

Who was the first weather forecaster?

Benjamin Franklin is often credited with making the first long-term weather predictions in his *Poor Richard's Almanac*. However, these forecasts were based primarily on *folklore* rather than weather data. Nevertheless, Franklin may have been the first to document that storm systems move. In 1743, while living in Philadelphia, rain prevented Franklin from viewing an eclipse. Through later correspondence with his brother, he learned that the eclipse could be seen in Boston, but within a few hours, that city also experienced rainy weather. This led Franklin to conclude that the storm that obscured the eclipse in Philadelphia moved up the east coast to Boston.

Concept Checks 12.2

- What agency is responsible for gathering weather information on a global scale?
- List the main sources of *surface* weather data.
- What is the primary source of weather data used to plot upper-level weather charts?

12.3 Weather Maps: Depictions of the Atmosphere

LO 3 Interpret what a particular pattern in the flow aloft indicates about surface weather.

Once the vast amount of observational data is collected, it is displayed on a series of computer-generated weather maps. Meteorologists then fine-tune the maps to provide the most accurate description (analysis) of the current weather conditions possible. This task, called **weather analysis**, includes a detailed examination of the troposphere, where the day-to-day weather occurs. More than 200 surface maps and upper-level charts covering several levels of the atmosphere are produced daily by the NWS and its forecast centers.

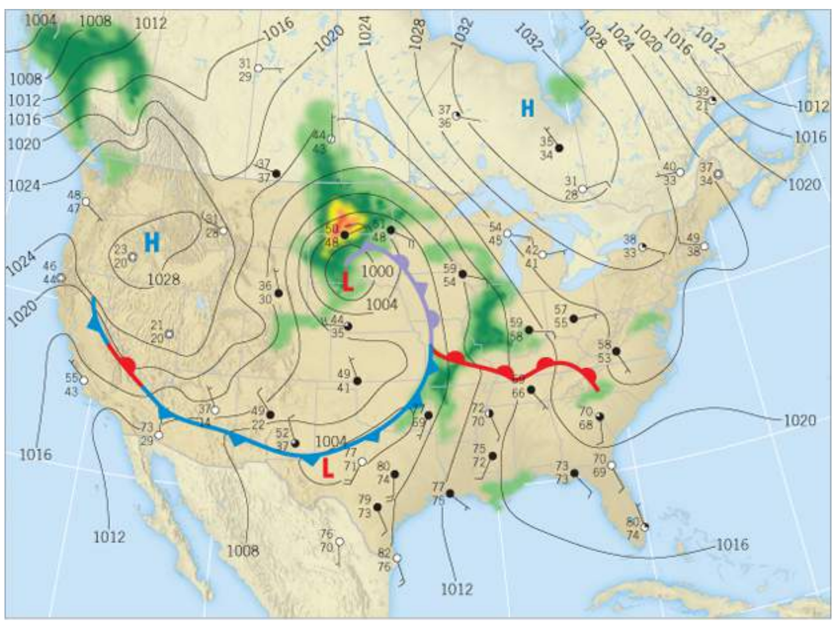
The goals of weather analysis include locating developing weather systems, identifying frontal boundaries, and assessing the potential for atmospheric instability that may result in severe storms.

Surface Weather Maps

A traditional surface weather map symbolically represents the current state of the atmosphere near Earth's surface. To the trained eye, these weather maps provide a snapshot of surface conditions including temperature, humidity, wind, and cloud cover (Figure 12.6). Surface weather maps provide a view of weather elements over a geographical area at a specified time based on information from ground-based observation stations. Humans previously completed the tedious task of plotting weather data, but computers now plot the vast array of data systematically.

Figure 12.6 Simplified surface weather map

Surface weather map for 7:00 a.m. Eastern Standard Time, depicting a well-developed middle-latitude cyclone.



Surface weather maps that include the locations of pressure systems and fronts are called **surface weather analysis (or simply, surface analysis)**. The analysis phase involves taking the vast array of weather data and organizing it so that users can discern large-scale weather patterns. This process begins by drawing isobars on the map. Once the isobars are drawn, one can immediately locate regions of high and low pressure. Adding fronts is the next step in producing a surface weather analysis. Advances in computing power make it possible to overlay satellite and radar images over surface maps to provide the best possible description of current atmospheric conditions.

Appendix B (pages A-5–A-10) provides an explanation of how surface weather maps are constructed and decoded.

Upper-Level Weather Charts

Chapter 9 established the strong connection between flow of the westerlies aloft and cyclonic disturbances at the surface. To understand the development of thunderstorms or the formation and movement of midlatitude cyclones, meteorologists must know what is occurring aloft.

Upper-air charts are generated twice daily, at 0000 and 1200 UTC. These charts are drawn at 850-, 700-, 500-, 300-, and 200-millibar (mb) pressure levels as height contours (in meters or tens of meters), which are analogous to isobars used on surface maps. Like surface maps, upper-level charts are often referred to as *analysis charts*, or *upper-level analyses*.

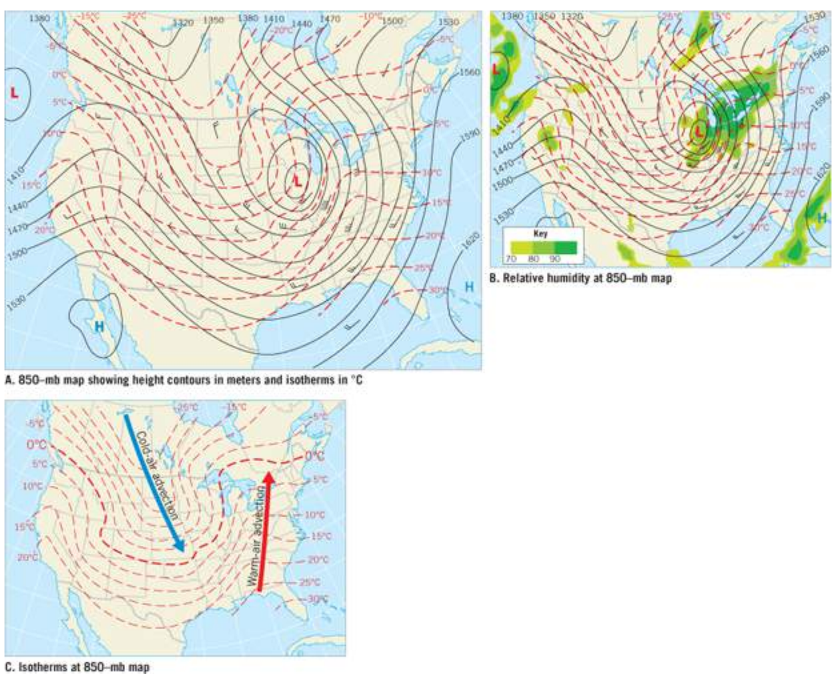
Upper-level charts may also contain *isotherms* (lines of equal temperature) depicted as dashed lines, and some show humidity as well as wind speed and direction.

850-Millibar Charts

Figure 12.7A is an 850-mb map showing height contours using solid black lines at 30-meter intervals and dashed red isotherms labeled in degrees Celsius. Wind data are plotted using black flags. If relative humidity is included, humidity levels above 70 percent are indicated in shades of green, as shown in Figure 12.7B. These charts may appear complicated because of the large amount of data they display, but they are nonetheless quite useful for predicting changes in surface conditions.

Figure 12.7 **Typical 850-mb maps**

A. The solid lines are height contours spaced at 30-meter intervals, and the dashed lines are isotherms in degrees Celsius. **B.** Regions where the relative humidity is greater than 70 percent are depicted in shades of green. **C.** Areas of warm- and cold-air advection are shown with colored arrows.



The 850-mb map depicts the atmosphere at an average height of about 1500 meters (1 mile) above sea level. In areas near sea level, the height of the 850-mb chart is near the top of *planetary boundary layer*—the lowest layer of the troposphere, where friction and turbulence are most prevalent. Within the boundary layer, daily temperature fluctuations are strongly influenced by the warming and cooling of Earth's surface. In high-elevation areas such as Denver, Colorado, the 850-mb level represents surface conditions, and the 850-mb chart is used as a proxy for (in place of) the surface map.

Forecasters regularly examine the 850-mb map to locate areas of possible *cold-air* or *warm-air advection*. Cold-air advection occurs when winds blow horizontally across isotherms from colder to warmer areas. Figure 12.7C, a simplified version of Figure 12.7A, shows a blast of cold air moving south from Canada into the Great Plains. As you might expect, cold air advection results in cooler temperatures. Cold air advection at low levels also causes air aloft to sink, which enhances atmospheric stability. Recall that stability caused by sinking air is associated with clearing skies, which is expected with the passage of a cold front.

> The 850-millibar chart shows conditions near the surface, including warm and cold air advection.

Also notice in Figure 12.7C that warm air is moving from the Gulf of Mexico toward the northeast. This means that the eastern seaboard of the United States will experience rising temperatures over the next day or so. Warm-air advection is also generally associated with widespread uplift in the lower troposphere because warm air is less dense than the cold air it replaces and causes the air aloft to rise. If humidity in the region of warm-air advection is relatively high, as shown in Figure 12.7B, then lifting could result in cloud formation and possibly precipitation.

Temperatures at the 850-mb level provide other useful information. During winter, for example, forecasters use the 0°C isotherm as the boundary between areas of rain and areas of snow or sleet. Further, because air at the 850-mb level does not experience the daily cycle of temperature changes that occurs at the surface, these maps provide a way to estimate the daily maximum surface temperature. In summer, the maximum surface temperature is usually 15°C (27°F) higher than the temperature at the 850-mb level. In winter, maximum surface temperatures tend to be about 9°C (16°F) warmer than at the 850-mb level, and during the fall and spring, this difference is about 12°C (22°F).

700-Millibar Charts

The 700-mb flow, which occurs about 3 kilometers (2 miles) above sea level, serves as the steering mechanism for ordinary thunderstorms that tend to occur in the warm summer months. Thus, winds at this level are used to predict the movement of these storms.

A generally accepted "rule of thumb" used with 700-mb maps is that when air temperatures are 14°C (57°F) or higher at that level, thunderstorms will not develop. A warm 700-mb layer acts as a lid that inhibits the upward movement of warm, moist surface air that might otherwise rise to generate towering cumulonimbus clouds. The warm conditions aloft are usually caused by general subsidence associated with a strong high-pressure center.

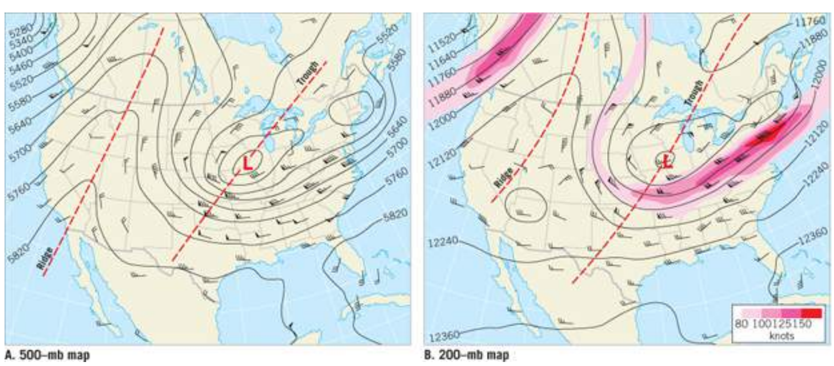
> The 700-millibar chart shows steering winds for thunderstorms.

500-Millibar Charts

The 500-mb level is located approximately 5000 meters (18,000 feet) above sea level—where about half of Earth's atmosphere is below this altitude and half is above. Notice in the example shown in Figure 12.8A that a large trough occupies much of the eastern United States, whereas a ridge is influencing the western states. Troughs indicate the presence of a storm at midtropospheric levels, whereas ridges are associated with clear, dry weather. A forecast predicting that a trough will increase in strength is an indication that a storm is likely to intensify.

Figure 12.8 Comparing 500- and 200-millibar upper-level charts

These charts show the flow pattern aloft on the same time and date but at different heights. **A.** Notice the well-developed trough of low pressure over central and eastern North America on the 500-millibar chart, and a ridge of high pressure positioned over the western portion of the continent. Height contours are spaced at 60-meter intervals. **B.** This 200-millibar chart shows the location of the jet stream (pink) and a jet streak (reddish). Height contours are spaced at 120-meter intervals.



> The 500-millibar chart is used to forecast the direction a midlatitude cyclone is expected to travel.

Forecasters find 500-mb charts useful tools for estimating the movement of surface cyclonic storms. These important weather producers tend to travel in the direction of the airflow at the 500-mb level, but at roughly a quarter to half the wind speed. Sometimes an upper-level low (shown as a closed contour in Figure 12.8A) forms within a trough. These lows are associated with counterclockwise rotation and significant vertical lifting, typically resulting in heavy precipitation.

300- and 200-Millibar Charts

Two of the regularly generated upper-level maps, the 300-mb and 200-mb charts, represent zones near the top of the troposphere. These are the levels at which the details of the *jet stream* can best be observed (Figure 12.8B). Recall that jet streams are high-velocity rivers of air that often flow around the globe in the midlatitudes. The polar jet stream, which influences midlatitude weather, tends to be located above the boundary between warm surface air and cold surface air.

Because the polar jet stream is lower in winter and higher in summer, 300-mb maps are most useful for interpreting it during winter and early spring, whereas 200-mb maps are most useful during the warm season. At these altitudes, about 12,000 meters (40,000 feet), temperatures can reach a frigid –55°C (–56°F).

> The 300- and 200-millibar charts show the location of the jet stream, which marks the boundary between surface warm and cold air.

The 300- and 200-mb maps usually contain **isotachs**, lines of equal wind speed, to show airflow aloft. Areas exhibiting the highest wind speeds, usually above 100 miles per hour, may also be colored as shown in Figure 12.8B. These segments of higher-velocity winds found within the jet stream are called **jet streaks**. Air that is entering a jet streak speeds up—just as a car merging onto an interstate highway speeds up to move into the flow of traffic. Conversely, air that is leaving a jet streak slows. These areas of acceleration and deceleration, coupled with the curving flow aloft, cause air to pile up in some areas (convergence) and spread out (divergence) in others. Divergence aloft leads to rising air, which supports surface convergence and cyclonic development (see Figure 9.11). By contrast, convergence aloft tends to weaken surface cyclones and causes them to dissipate.

Locating the position of the jet stream on these upper-air charts also aids in forecasting severe weather. Severe thunderstorms tend to develop near the jet stream, where winds near the top of the storm may be two to three times as fast as winds near the base. This difference in wind speed tilts the thunderstorm as it grows vertically, separating the area of updrafts from the area of downdrafts (see Figure 10.6,). This tilting prevents the rising cells of warm moist air from being canceled by the cool downdrafts, allowing the storm to grow dramatically in intensity.

The Connection Between Large-scale Flow Aloft and Surface Weather

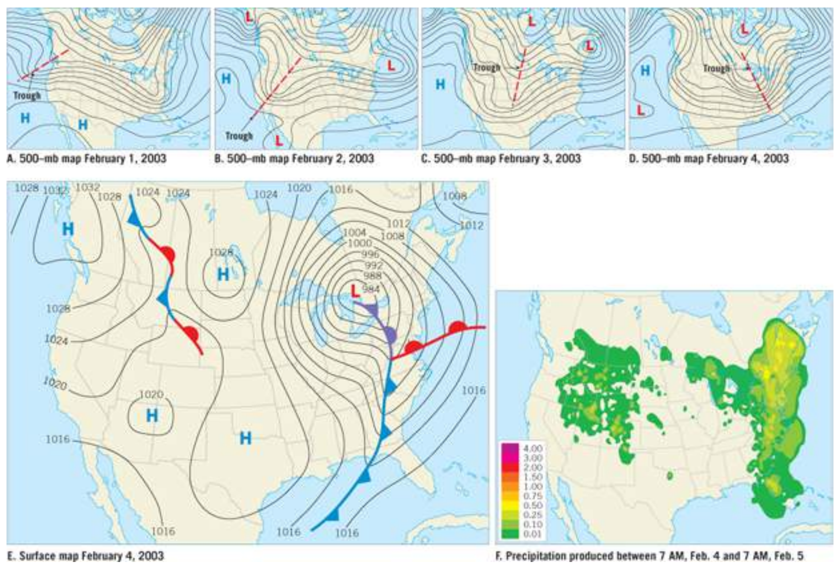
Occasionally, the flow within the westerlies is directed along a relatively straight path from west to east, a pattern referred to as **zonal**. Storms embedded in this zonal flow move quickly across the country, particularly in winter. This situation results in rapidly changing weather, with periods of light to moderate precipitation followed by brief periods of fair weather.

More often, however, the flow aloft consists of long-wave troughs and ridges that have large components of north–south (**meridional**) flow. Typically, these airflow patterns slowly drift from west to east, but they occasionally stall and may even reverse direction. As this wavy pattern gradually migrates eastward, cyclonic storms embedded in the flow are carried across the country.

Figure 12.9 shows a trough that was centered off the U.S. Pacific coast on February 1, 2003. Over the next 4 days (FIGURE 12.9A–12.9D), the trough intensified as it moved eastward into the Ohio Valley. This change in intensity is shown by the height contours, which are more closely packed around the trough on February 4 than on February 1. Embedded in this upper-level trough was a cyclonic system, which grew into the major storm shown on the surface map in Figure 12.9E. By February 5, this disturbance generated considerable precipitation over much of the eastern United States (FIGURE 12.9F).

Figure 12.9 **The connection between the flow aloft and surface weather**

A–D. The movement and intensification of an upper-level trough over a 4-day period from February 1 to February 4, 2003. **E.** This surface map shows a strong cyclonic storm that formed earlier in the week and moved, in conjunction with the trough, to the position shown on the February 4 map. **F.** Precipitation map shows precipitation amounts that fell from 7:00 a.m. February 4 to 7:00 a.m. February 5, shown in inches.



In general, meridional flow aloft has the potential for generating extreme conditions. During winter, strong troughs tend to spawn large snowstorms, whereas in summer they are associated with severe thunderstorms and tornado outbreaks. By contrast, high-amplitude ridges are associated with record heat in summer and tend to bring mild conditions in winter.

> Meridional flow aloft is often associated with extreme weather at the surface.

Sometimes these “looped” patterns stall over an area, causing surface patterns to change minimally from one day to the next or, in extreme cases, from one week to the next. Locations in and just east of a stationary or slow-moving trough experience extended rainy or stormy periods, while areas in and just east of a stagnant ridge experience prolonged periods of unseasonably warm, dry weather.

Concept Checks 12.3

- What information can forecasters glean from 850-mb maps? 700-mb? 500-mb? 300- or 200-mb?
- Explain the difference between zonal and meridional airflow.

12.4 Modern Weather Forecasting

LO 4 Explain the basis of numerical weather prediction.

Until the late 1950s, all weather maps and charts were plotted manually and served as the primary tools for making weather forecasts. Forecasters used various techniques to extrapolate future conditions from the patterns depicted on the most recent weather maps. Today, we use computers to plot data and produce weather maps. Computers have improved the accuracy and detail of weather forecasts and have lengthened the period for which useful guidance can be given.

Numerical Weather Prediction

Numerical weather prediction is a technique that employs complex computer programs, called **forecast models**, to make a weather forecast. (The word *numerical* is somewhat misleading because all types of weather forecasting are based on some quantitative data and, therefore, could fit in this category.) Numerical weather prediction relies on the fact that the behavior of atmospheric gases is governed by a set of fundamental physical principles or laws (for example, the *ideal gas law* and the *laws of thermodynamics*) that can be expressed as mathematical equations. Meteorologists begin by plugging current atmosphere conditions, such as temperature, pressure, and wind, into a forecast model run on supercomputers. The output, a description of the future state of the atmosphere, is called a *weather forecast*.

> Numerical weather prediction employs complex computer programs, called *forecast models*, to make weather forecasts.

The NWS utilizes several different numerical models, including global and regional forecast models. Other organizations, such as the Canadian Meteorological Centre (CMC), the European Centre for Medium-Range Forecasting (ECMWF), and the United Kingdom Met Office (UKMET), as well as the U.S. military, also employ excellent global and regional forecast models. Most of these forecast products are easily accessed on the Internet.

Numerical weather prediction uses highly refined computer models that attempt to mimic the behavior of the "real" atmosphere. All numerical models employ the same governing mathematical equations, but they apply the equations and the parameters in different ways. For example, each model is designed to cover a specific area. Models that are considered "global" in scale usually cover one hemisphere, whereas others are "regional," covering areas such as North America or Europe.

Each model has a three-dimensional grid consisting of a large number of points, called *grid points*, separated by a defined distance. A high-resolution model has grid points that are generally separated by less than 5 kilometers, whereas a low-resolution model might have data points located more than 300 kilometers apart. Regardless of area covered or model resolution, all numerical weather prediction models are complex and require considerable computer resources to operate.

Steps in Numerical Prediction

Numerical weather forecasting begins by assigning current weather measurements (temperature, wind speed, humidity, and pressure) to each of the grid points in the forecast model. This is done by gathering data from as many locations as possible and interpolating these data to other selected locations. This set of values represents the atmospheric conditions at the start of the forecast.

Next, a computer simulation solves each equation for as many as 50 levels of the atmosphere—a process referred to as a *computer run*. After literally billions of calculations, a forecast of how these basic weather elements are expected to change over a short time frame (perhaps only 5 to 10 minutes) is generated. When the new values have been calculated, the process begins again, generating a forecast for the next 5 to 10 minutes. These steps are repeated numerous times until the end of the forecast period. Some models produce forecasts on an hourly basis (out to perhaps 12 hours), while other models generate forecasts every 6 hours —with coverage of up to 2 days or longer.

Model Output Statistics (MOS)

Once generated, statistical methods are used to modify machine-generated numerical forecasts by making comparisons of the accuracy of previous forecasts. This approach, known as **Model Output Statistics** (**MOS**, pronounced "moss"), attempts to correct for errors the model tends to make consistently. For example, certain forecast models may typically predict too much rain, overly strong winds, or temperatures that are too high or too low. MOS also takes into account local conditions that are not built into the forecast models. MOS forecasts form the baseline on which NWS and private-sector forecasters attempt to improve.

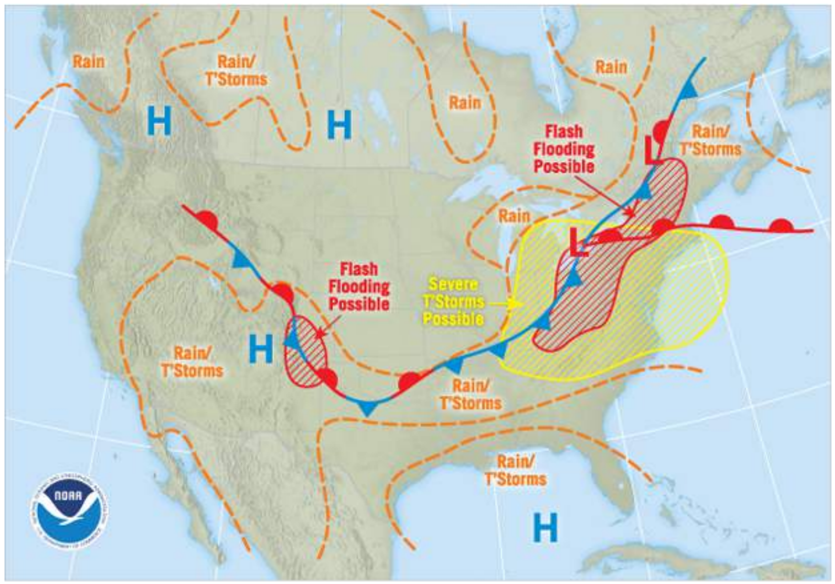
> Model Output Statistics (MOS) corrects bias in the numerical model output.

After the highly refined MOS forecasts are generated, forecasters determine how well they matched the actual weather conditions that developed during the forecast period. This important *postprocessing phase* is necessary for continually adjusting numerical models and improving their predictability.

Using various mathematical models, the NWS produces a variety of forecast charts. Because these machine-generated maps predict atmospheric conditions at some future time, they are often referred to as **prognostic charts, or simply progs**. Some forecast charts depict surface weather features such as fronts, high- and low-pressure systems, and expected weather events, as shown in Figure 12.10. Others depict a single weather element such as maximum temperature (see Figure 12.24), while still others show the airflow pattern aloft at various levels. These forecast products, although indispensable, represent only one step in the complex process of making regional and local forecasts.

Figure 12.10 **Weather forecast for Sunday, July 27, 2014**

This generalized weather forecast was prepared and disseminated by the Weather Prediction Center of the NCEP. It includes areas of high and low pressure and frontal types and locations, and it outlines areas that have potential for precipitation and severe weather.



Why Are Numerical Forecasts Imperfect?

Despite the sophistication of numerical models, most still produce forecast errors. Factors affecting their accuracy include the inadequate representation of physical processes operating in the atmosphere, errors or omissions in the initial observations, and the inability of models to depict small-scale weather elements, such as tornadoes.

Although the models are grounded on sound physical laws and capture the major characteristics of the atmosphere, they are designed to simplify the intricacies of a very complex system. The topography in the forecast area is one example of a variable that is not accurately represented in current numerical models. As a result, humans perform the final steps in weather forecasting, using their experience and knowledge of meteorology as well as making allowances for known model shortcomings (Figure 12.11).

Figure 12.11 Meteorologist at the National Hurricane Center in Miami, Florida

This forecaster is examining satellite imagery of Hurricane Ivan as the eye crosses the Alabama coastline on September 16, 2004. Humans perform the final steps in weather forecasting, using their experience and knowledge of meteorology.

Ensemble Forecasting and Uncertainty

One of the most significant challenges for weather forecasters is the chaotic behavior of the atmosphere. Specifically, two very similar weather systems may, over time, develop into two very different weather patterns. One may intensify, becoming a major disturbance, while the other withers and dissipates. To demonstrate this point, Edward Lorenz at the Massachusetts Institute of Technology employed a metaphor known as the *butterfly effect*. Lorenz described a butterfly in the Amazon rain forest, fluttering its wings and setting into motion a subtle breeze that travels and gradually magnifies over time and space. Two weeks later this faint breeze has grown into a tornado over Kansas. Obviously, by stretching the point considerably, Lorenz tried to illustrate that a very small change in initial atmospheric conditions can dramatically affect the resulting weather pattern elsewhere.

To deal with the inherent chaotic behavior of the atmosphere, forecasters rely on a technique known as **ensemble forecasting**. Simply, this method involves producing a number of forecasts using the same computer model but slightly altering the initial conditions, while remaining within an error range of the observational instruments. Essentially, ensemble forecasting attempts to assess how the inevitable errors and omissions in weather measurements might affect forecast accuracy.

One of the most important outcomes of ensemble forecasts is the information they provide about forecast *uncertainty*. For example, a prognostic chart generated using the best available weather data might predict the occurrence of precipitation over a wide area of the southeastern United States within 24 hours. A meteorologist might run the same calculations several times in succession, each time making minor adjustments to the initial conditions. If most of these prognostic charts predict a pattern of precipitation in the Southeast, the forecaster will place a high degree of confidence in the forecast. However, if the progs generated by the ensemble method differ significantly from one run to the next, there will be far less confidence in the forecast.

> Ensemble forecasting allows meteorologists to assess uncertainty in a numerical forecast.

Concept Checks 12.4

- Briefly describe the basis of numerical weather prediction.
- What are prognostic charts?
- What additional information does an ensemble forecast provide over a traditional numerical weather prediction?

12.5 Other Forecasting Methods

LO 5 Distinguish among the various traditional methods of weather forecasting.

Although computer-generated prognostic charts form the basis of modern forecasting, other methods are available to meteorologists. Methods that have stood the test of time are used mainly to improve machine-generated forecasts, and they include persistence forecasting, climatological forecasting, the analog method, and trend forecasting.

Persistence Forecasting

Perhaps the simplest forecasting technique, **persistence forecasting** is based on the tendency of weather to remain unchanged for several hours or even days. If it is raining at a particular location, for example, it is reasonable to assume that it will still be raining in a few hours. Persistence forecasts do not account for possible changes in the intensity or direction of a weather system, nor can they predict the formation or dissipation of storms. Because of these limitations and the rapidity with which weather systems change, persistence forecasts usually diminish in accuracy within 6 to 12 hours, or 1 day at the most.

> Persistence forecasting assumes that the weather will not change over a specified time period.

Climatological Forecasting

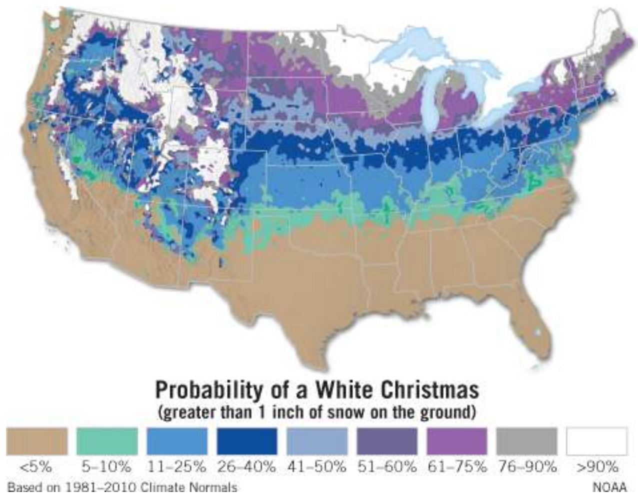
Climatological forecasting is another relatively simple way of generating forecasts using climatological data—average weather statistics accumulated over many years. For example, Yuma, Arizona, experiences sunshine approximately 90 percent of its daylight hours; thus, forecasters predicting sunshine every day of the year would be correct about 90 percent of the time. Likewise, forecasters in Portland, Oregon, would be correct about 90 percent of the time by predicting overcast skies in December.

> Climatological forecasting assumes that the average weather will prevail.

One interesting use of climatological data is for predicting a “white Christmas”—that is, a Christmas with inch or more of snow on the ground. As Figure 12.12 illustrates, northern Minnesota, Wisconsin, Michigan, New England, and the mountainous areas of the West have more than a 90 percent chance of a “white Christmas.” By contrast, southern Florida has a minuscule chance of experiencing snow for the holidays.

Figure 12.12 **Probability of a "white Christmas"**

The probability values are given as a percentage and represent the chance of a Christmas with at least 1 inch of snow on the ground.



Analog Method

A somewhat more complex way to predict the weather is by using the **analog method**, which is based on the assumption that weather repeats itself in a predictable way. Thus, forecasters attempt to find well-established weather patterns from the past that are similar to a current event. From such a comparison, forecasters predict how the current weather might evolve. The analog method was the backbone of weather forecasting before the advent of computer modeling, and an analog method called *pattern recognition* remains an important tool for improving short-range machine-generated forecasts.

> Analog forecasting assumes that weather repeats itself in a predictable way.

Trend Forecasting

The **trend forecasting** method involves determining the speed and direction of features such as fronts, thunderstorms, and areas of precipitation. Using this information, forecasters attempt to extrapolate the future position of these weather phenomena. For example, if a line of thunderstorms is moving northeastward at 35 miles per hour, a trend forecast would predict that the storm will reach a community located 70 miles to the northeast in about 2 hours.

> Trend forecasting assumes that weather systems will continue to move in the same direction and at the same rate.

Because weather events tend to increase or decrease in speed and intensity or change direction, trend forecasting is most effective over periods of just a few hours. Thus, it works particularly well for forecasting severe weather events that are expected to be short-lived, such as hailstorms, tornadoes, and downbursts, because warnings for such events must be issued quickly and must be site specific.

A type of trend forecasting, called **nowcasting**, is used to predict very short-lived (usually 6 hours), localized weather events. Using interactive computers capable of integrating data from multiple sources, nowcasting depends heavily on weather radar and geostationary satellites. Its primary use is to issue warnings of severe weather, such as tornadoes, hailstorms, and high winds (Figure 12.13).

Figure 12.13 Mesoscale phenomena such as this tornado are too small to appear on a prognostic chart

Detection of mesoscale weather events relies heavily on weather radar and geostationary satellites.

Concept Checks 12.5

■ If it is snowing today, what weather might be predicted for tomorrow if the persistence forecasting method is employed?

■ What term is applied to the very short-range forecasting technique that relies heavily on weather radar and satellites? What type of weather phenomena are typically forecast using this technique?

■ Which technique predicts the weather based on average weather statistics accumulated over many years?

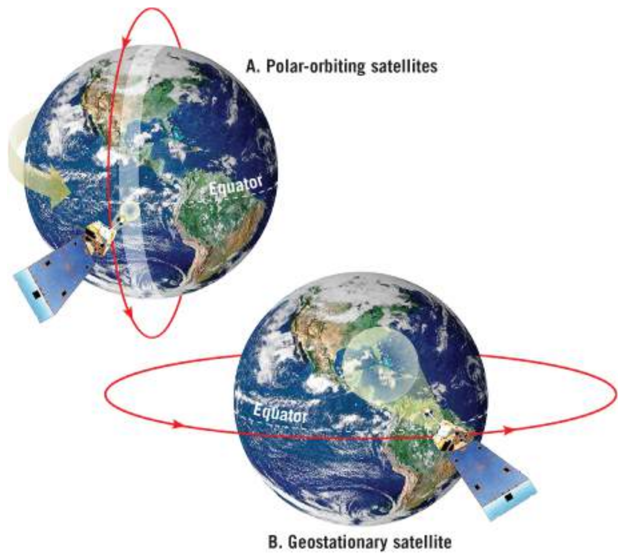
12.6 Weather Satellites: Tools in Forecasting

LO 6 Discuss the advantages and disadvantages of infrared, visible, and water-vapor imagery generated by weather satellites.

Meteorology entered the space age in 1960, when the first weather satellite, *TIROS* 1, was launched. *TIROS* 1, like other weather satellites in this series, was placed into a polar orbit—so that it circles Earth from roughly north to south (Figure 12.14A). **Polar-orbiting Operational Environmental Satellites (POES)** are low-flying satellites that orbit approximately 850 kilometers (530 miles) above Earth's surface 14 times daily. Earth's rotation causes these satellites to drift about 15° westward, recording a different view with each orbit. The POES system offers the advantage of recording images of the entire planet twice daily and covering a large region in a few hours. Also, because of their relatively low altitude, POES instruments obtain high-resolution images.

Figure 12.14 **Weather satellites**

A. Polar-orbiting satellites circle roughly over the North and South Poles. **B.** A geostationary satellite moves at the same rate that Earth rotates and remains stationary over a fixed position on Earth's surface.



Data from POES instruments support weather analysis and forecasting, climate research, global sea-surface temperature measurements, atmospheric soundings of temperature and humidity in cloudless areas, and cloud and precipitation monitoring. The data collected by POES instruments can be assimilated directly into numerical weather prediction models to help produce more reliable short- and medium-range forecasts. The NWS partners with a consortium of European nations so that at least two polar-orbiting satellites are operational at all times—one from the POES series and one European satellite from the MetOp series.

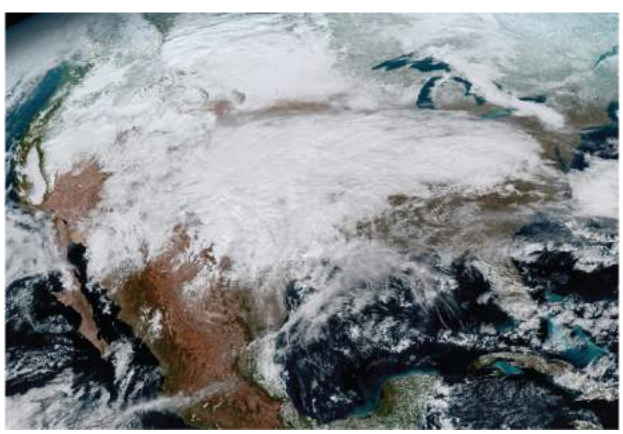
Another class of weather satellites, **Geostationary Operational Environmental Satellites (GOES)**, was first placed in orbit over the equator in 1966 (Figure 12.14B). As their name implies, GOES instruments remain fixed over a point on Earth because their rate of travel keeps pace with Earth's rate of rotation. In order to remain positioned over a given site, however, the satellite must orbit at a greater distance from Earth's surface (about 35,000 kilometers [22,000 miles]) than polar-orbiting satellites. At these higher altitudes, the GOES images obtained are less detailed than those captured by POES instruments.

The most recent generation in the GOES series, GOES-16, was launched in 2016. This two-satellite system, positioned at 75°W longitude and 137°W longitude, provides enhanced coverage of most of North America and surrounding water bodies. The GOES-16 provides higher resolution and more frequent updates than earlier GOES satellites.

Other countries, including a consortium of European countries, India, China, Japan, and Russia, also operate geostationary satellites. Collectively, these satellites easily track the movement of large weather systems, like the midlatitude cyclone shown in Figure 12.15, as they migrate across even the most remote portions of Earth. Geostationary satellites also play an important role in monitoring the development and movement of tropical storms and hurricanes.

Figure 12.15 Weather satellites are invaluable tools for tracking storm systems

This color composite image, produced by GOES-16, shows a severe storm that crossed North America causing freezing and icy conditions in Kansas and Nebraska on January 15, 2017.



Watch **Video: Modeling the Atmosphere on Your Desktop**

Types of Satellite Images

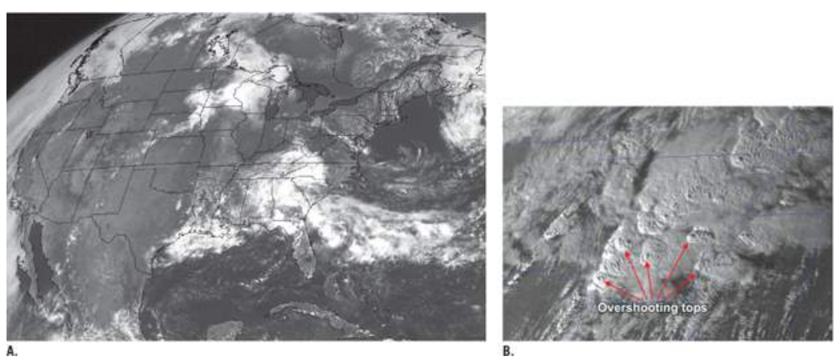
The most recent generation of weather satellites provides visible, infrared, and water-vapor images for North America and adjacent ocean areas. These satellite images can be seen on most TV weather broadcasts.

Visible Images

GOES are equipped with instruments that detect sunlight reflected from Earth, producing *visible light images* such as the one shown in Figure 12.16. Because visible light imagery records the intensity of light reflected from cloud tops and other surfaces, these images are similar to black-and-white photos of Earth. Clouds or snow- and ice-covered areas have high albedos and thus are strong reflectors of light. Thick clouds appear bright white, while thin clouds are dull white. Land surfaces appear dark gray because they reflect less light than clouds, whereas the oceans, which reflect very little light, appear nearly black.

Figure 12.16 Visible light images

A. Visible light image provided by a GOES of cloud distribution about midday on July 15, 2011. This image records sunlight reflected off various Earth surfaces and appears much like a black-and-white image. **B.** Close-up visible image centered on the state of Iowa shows towering cumulonimbus clouds with overshooting tops.



> Visible satellite imagery is used to determine cloud locations and thickness during the day.

Visible images are useful in identifying cloud shapes, organizational patterns, and cloud thickness. In general, the thicker the cloud, the brighter it appears in the image. Cumulonimbus clouds have a bumpy appearance, whereas stratus clouds form a continuous flat-looking blanket. Figure 12.16B is a visible light image that shows towering cumulonimbus clouds with overshooting tops.

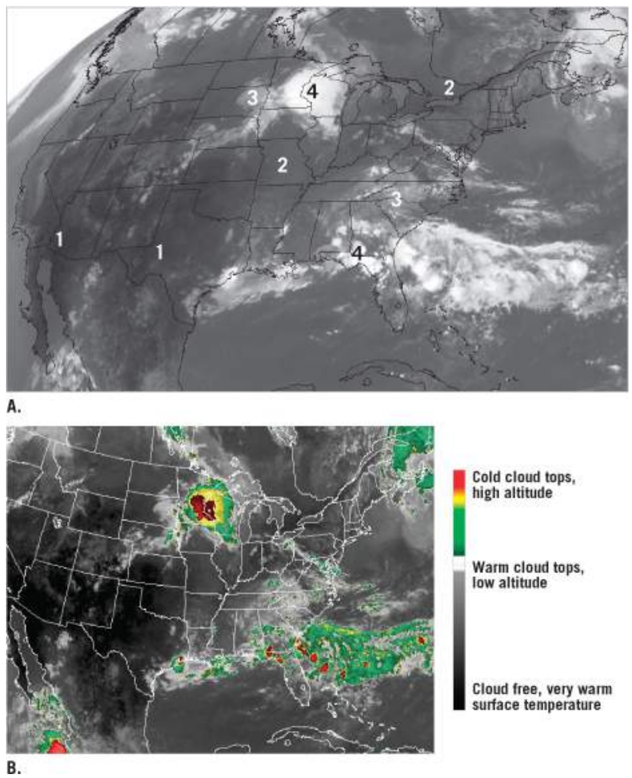
Infrared Images

In contrast to visible images, *infrared images* are obtained from radiation emitted (rather than reflected) from objects and, when compared to visible images, are especially useful in determining which clouds are most likely to produce precipitation and/or stormy conditions. Infrared satellite images are usually generated by computers programmed to display warm objects, such as Earth's surface, in black and colder objects, such as high cloud tops, in white. Because high cloud tops are colder than low cloud tops, towering cumulonimbus clouds that usually generate heavy precipitation appear very bright, whereas midlevel clouds appear light gray. Low fair-weather cumulus clouds, stratus clouds, and fog are all relatively warm and therefore appear dark gray or may not be discernable on infrared images.

Compare Figure 12.16A, a visible image, to Figure 12.17A, which is an infrared image of the same region. Both images were acquired on a very hot summer day in 2011 that produced thunderstorms over parts of Minnesota and Wisconsin, as well as in the Southeast. As you can see, the clouds over eastern South Dakota that appear white on the visible image appear gray on the infrared image. Middle clouds at 2000–6000 meters blanket this area. By contrast, the clouds over eastern Minnesota and western Wisconsin appear bright in both the visible and infrared images. This region has towering cumulonimbus clouds and was experiencing air-mass thunderstorms that brought heavy rain to the area. The areas of isolated storm cells in the southeastern United States are also easily identifiable on the infrared image in Figure 12.17A.

Figure 12.17 **Infrared satellite images**

A. Infrared image provided by a GOES about midday on July 15, 2011. Numbers 1–4 in this infrared image identify areas that (1) are cloud free; (2) contain low clouds (cumulus) with cloud tops below 2000 meters; (3) are blanketed by cloud tops between 2000 and 6000 meters; and (4) feature high, cold cloud tops associated with towering cumulonimbus clouds and thunderstorms, measured by the infrared sensor. **B.** Color-enhanced infrared image for the same period of time as part A. The dark-reddish color indicates the location of towering cumulonimbus clouds.



> Infrared satellite imagery is used to determine cloud height during both day and night.

To help meteorologists interpret infrared images, false colorization is sometimes used. The coldest, and thus highest, cloud tops, which typically identify areas of heavy precipitation, are shown in strong colors. Notice the reddish areas over the Minnesota–Wisconsin border in Figure

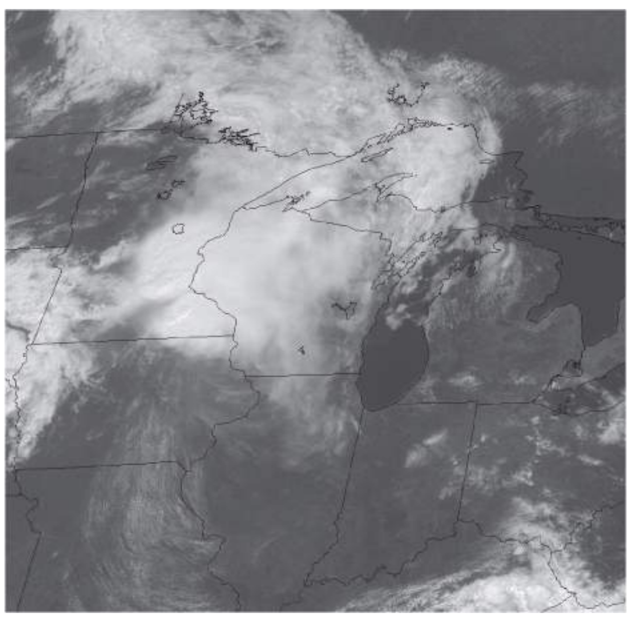
12.17B. This is the same area that appears as bright white in the infrared image in Figure 12.17A.

Visible Versus Infrared Imagery

A major advantage of infrared imagery is its ability to detect energy radiated skyward both day and night. As a result, the movement of storms can be monitored 24 hours a day. However, an advantage of visible images is their high resolution—which makes detection of smaller features possible. Figure 12.18 is a close-up of a portion of the visible image in Figure 12.16. Notice the bands of fair-weather cumulus clouds over eastern Missouri and Iowa and the bumpy tops of the developing cumulonimbus clouds over southeastern Minnesota. Visible images are better for showing cloud patterns and storm systems such as midlatitude cyclones and hurricanes.

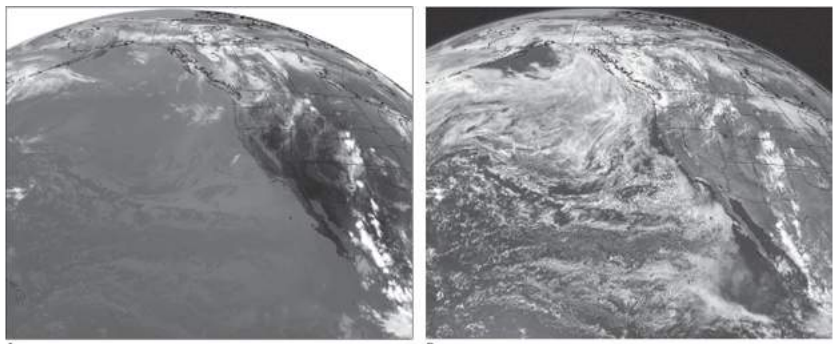
Figure 12.18 Close-up GOES visible image obtained July 15, 2011

This visible image centers around Wisconsin and was obtained on the same date and time as the images in Figures 12.16 and 12.17. The bright clouds over the Minnesota–Wisconsin border were producing heavy precipitation when this image was obtained.



Eye on the Atmosphere 12.1

These satellite images of the eastern Pacific and a portion of North America were obtained at the same time on July 14, 2001. One of these is an infrared image, and the other is a visible light image.



A. B.

Apply What You Know

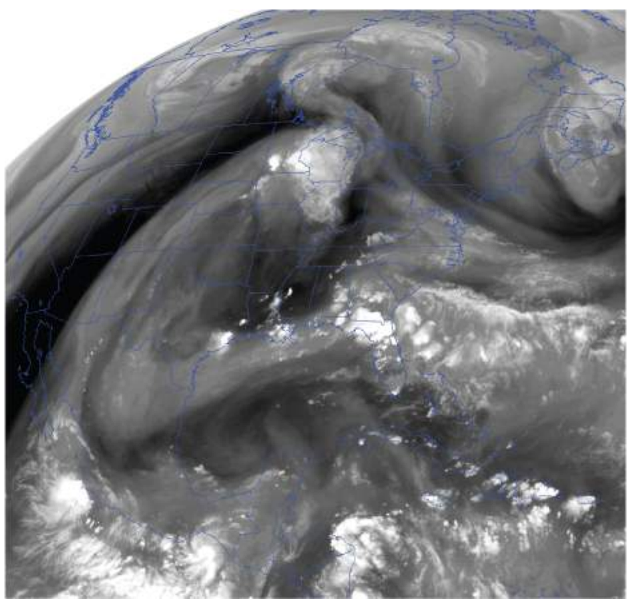
1. On which image (A or B) are the cloud shapes and patterns more easily recognized?
2. Which one of these images was obtained using infrared imagery? How can you tell?
3. What types of clouds are found in the western Great Plains (just east of the Rockies)?
4. Are the clouds over the eastern Pacific Ocean mainly high clouds or middle- to low-level clouds?

Water-Vapor Images

Water-vapor images provide yet another way to view Earth. Most of Earth's radiation with a wavelength of 6.7 micrometers is emitted by water vapor. Satellites equipped with detectors for this narrow band of radiation are, in effect, mapping the concentration of water vapor in the middle and upper troposphere. Bright-white areas in Figure 12.19 represent regions of high water-vapor concentration, whereas dark areas indicate drier air. Because most fronts occur between air masses having contrasting moisture conditions, water-vapor images are valuable tools for locating frontal boundaries.

Figure 12.19 Water-vapor image obtained July 15, 2011

The brighter the white, the greater the atmosphere's water-vapor content. Black areas are driest.



Concept Checks 12.6

- How do satellites help identify clouds that are likely to produce precipitation?
- What advantage do geostationary satellites have over polar-orbiting satellites? Name one disadvantage.
- What advantages do infrared images have over visible light images? Name one disadvantage.

12.7 Types of Forecasts

LO 7 Compare and contrast qualitative and quantitative weather forecasts. Differentiate between weather forecasts and 30- and 90-day outlooks.

Because many disasters are weather related, probably the most significant professional contribution of a forecaster is issuing a forecast, or warning, of an impending severe weather event.

Qualitative Versus Quantitative Forecasts

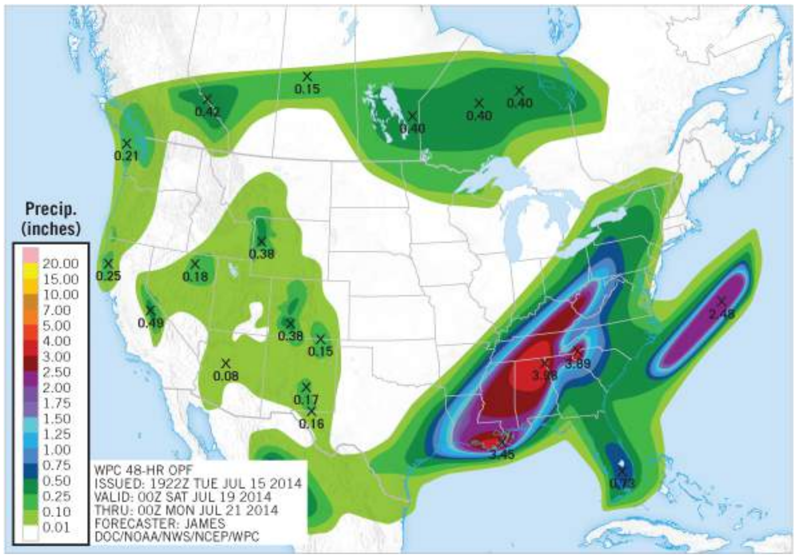
Most forecasts are one of two types—either qualitative or quantitative.

A **qualitative forecast** describes an aspect of the weather that can be observed but not easily measured, or quantified. Examples include forecast statements like these: "partly cloudy in the morning followed by gradual clearing"; "gusty winds expected in the afternoon"; and "scattered thunderstorms possible after sunset." Qualitative forecasts, although not easy to assess, can be very informative to the public.

Quantitative forecasts, by contrast, deal with measurable weather data. An example is a forecast predicting maximum and minimum temperatures. Figure 12.20 shows a **Quantitative Precipitation Forecast (QPF)** that depicts the amount of liquid precipitation (in inches) expected to fall over an area within a defined period of time. Because precipitation can vary significantly over short distances, especially during thunderstorms, these forecasts are given as averages for a given area. Like most other forecasts issued by the NWS, precipitation forecasts can be easily accessed on the Internet.

Figure 12.20 **Quantitative Precipitation Forecast (QPF)**

This QPF depicts the amount of liquid precipitation expected to fall within a 48-hour period. Precipitation can vary significantly over short distances, especially during thunderstorms, so these forecasts are given as averages. Locations that are expected to receive the largest amount of precipitation (in inches) are marked with the letter *X*.



> The National Weather Service issues both qualitative and quantitative forecasts.

The only NWS-issued forecast that is given as a *percentage probability* is precipitation. These forecasts, referred to as **Probability of Precipitation (PoP)**, are often expressed something like this: "... chance of rain 40 percent" or "... a 40 percent chance of thunderstorms." What does 40 percent mean? Will it rain 40 percent of the time, or will it rain over 40 percent of the forecast area? Neither. The PoP describes the chance of precipitation occurring in any particular location within the forecast area. PoP is defined as:

$$\text{PoP} = (C \times A) \times 100\,\text{percent}$$

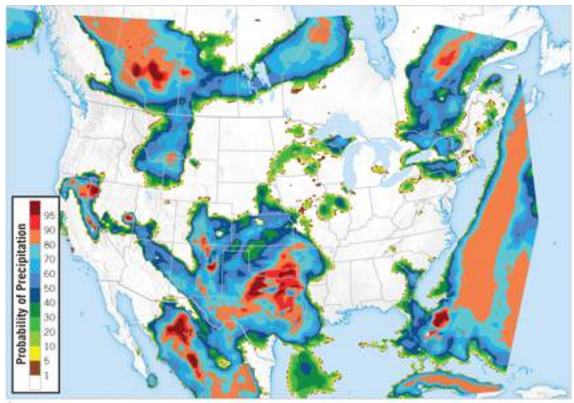
where *C* is the *confidence* that precipitation will occur *somewhere* in the forecast area, and *A* equals the *percentage of the area* that will receive measureable precipitation, if it occurs at all.

For example, if the forecaster expresses confidence that there is a 50 percent chance of precipitation in the forecast area, and also that if rain occurs, it will produce measurable precipitation over 80 percent of the area, the PoP (chance of rain) will be 40 percent (PoP = (0.5 × 0.8) × 100 percent = 40 percent). The NWS explains this as a 40 percent chance that precipitation will occur at any given point in the forecast area. Another way to express "40 percent chance of rain" is "on *average*, for all points in the area during the forecast period (usually 12 hours), the chance that rain will occur is 40 percent."

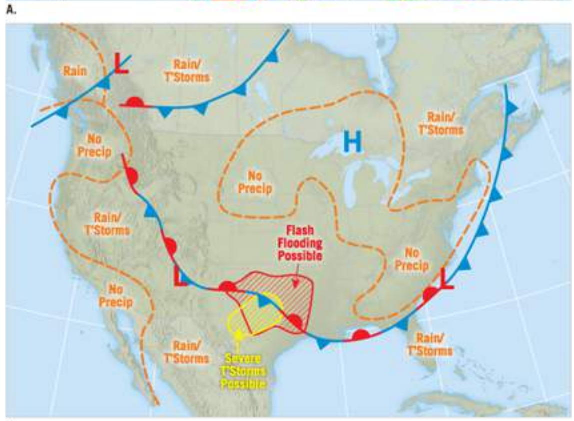
The NWS also produces another type of probability of precipitation forecast for the continental United States and surrounding areas in 6- and 24-hour increments, shown in Figure 12.21A. The region under a flood warning (Figure 12.21B) corresponds closely to the area on the precipitation map with a high probability of precipitation.

Figure 12.21 **Probability of precipitation forecast map**

A. Notice the area in northeastern Texas and adjacent states that has a high probability of receiving precipitation over the next 6 hours. Compare this area to the region in B issued for that same date. **B.** The region under a flash flood warning on the weather map corresponds closely to the region on the precipitation map with a high probability of precipitation.



A.



B.

Short- and Medium-Range Forecasts

The tools that forecasters use depend largely on how far into the future the forecast extends. The NWS defines weather forecasts based on time, as follows:

- Short-range forecasts extend up to 48 hours (2 days).
- Medium-range forecasts cover periods extending about 3 to 7 days into the future.
- Long-range forecasts are for periods beyond 7 days and have no outer time limit.

As described earlier, *nowcasting*, the shortest forecast period, extends to up to about 6 hours. This includes forecasting weather phenomena such as tornadoes and thunderstorm downbursts that cannot be predicted using numerical forecasting techniques (see Figure 12.13). To make these very short-range forecasts, meteorologists rely heavily on weather radar and satellite images.

Short-range forecasts that extend from the present out to 2 days are based on numerical forecasting techniques. Earlier we discussed how forecasters use their knowledge of typical model behavior and expertise to improve numerical forecasts. They must also consider average climatic conditions, microclimates that may exist, and local geographic variations within the forecast area. For example, Denver, situated along the foothills of the Rockies, often has very different weather from Aspen, located in the heart of the Rockies—even though both are in the same forecast region.

Numerical models have also proved valuable in producing medium-range (3- to 7-day) forecasts. As you would expect, these forecasts are not as reliable as short-range forecast, but they have improved significantly—so much so that the NWS is considering extending medium-range forecasts out to 10 days.

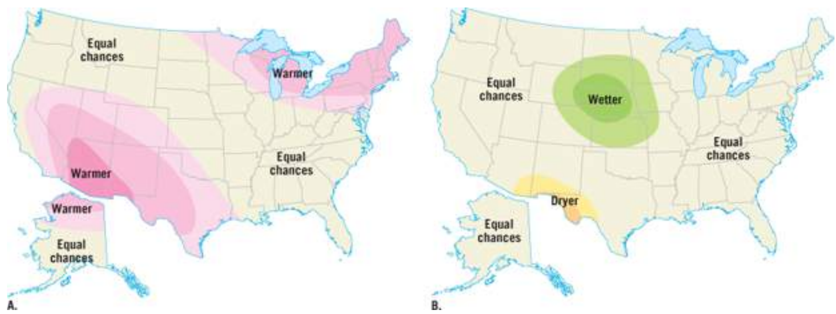
Long-Range Outlooks

Long-range forecasts extending to 2 weeks are generated by the **Climate Prediction Center (CPC)** of the NWS. These forecasts depend on a combination of numerical and statistical forecast guidance. The CPC is also responsible for producing monthly and seasonal (3-month) weather maps for temperature and precipitation called *30-* and *90-day outlooks*. These are not typical weather forecasts; instead, they offer insights into whether it will be drier or wetter and colder or warmer than normal in a particular region of the country.

A series of 13 90-day outlooks are produced in 1-month increments. The series begins with the outlook for the next 3 months—for example, September, October, and November. Next, a separate 90-day outlook for the period beginning 1 month later (October, November, and December) is constructed. Figure 12.22 shows the temperature and precipitation 90-day outlooks issued for September, October, and November 2011. The temperature outlook for this period calls for warmer-than-usual conditions across much of the southwestern, north-central, and northeastern United States (Figure 12.22A). The remainder of the country is labeled “equal chances,” which indicates that there are no climatic signals for either above- or below-normal conditions during the forecast period. The precipitation outlook shown in Figure 12.22B calls for wetter-than-normal conditions across most of Kansas, Nebraska, and South Dakota, whereas drier-than-normal conditions are expected in a portion of the Southwest from Texas to southeastern Arizona.

Figure 12.22 Extended forecast (90-day outlook) maps

These maps depict the **A.** temperature and **B.** precipitation outlooks for September, October, and November 2011. "Equal chances" means no climatic signals for either above- or below-normal conditions.



Monthly and seasonal outlooks of this type are generated using a variety of criteria. Meteorologists consider each region's climatology—the 30-year average of variables such as temperature and precipitation. Factors such as snow and ice cover in the winter and persistently dry or wet soils in the summer are incorporated. Forecasters also take into account current temperature and precipitation patterns. For example, during 2011 and a few preceding years, the U.S. Southwest experienced below-normal precipitation. Based on climatological data, the weather patterns that produce these conditions tend to gradually shift toward the norm rather than change abruptly. Thus, forecasters predicted that this below-normal trend would continue for at least the first several months of 2012.

Recently, sea-surface temperatures in the equatorial Pacific Ocean have been valuable in forecasting temperature and precipitation patterns in various locations around the globe—particularly in the winter season. For more on this relationship, see the section "El Niño, La Niña, and the Southern Oscillation" in Chapter 7.

Despite improved seasonal outlooks, the reliability of extended forecasts has been disappointing. Although some accuracy can be achieved during the late winter and late summer, outlooks prepared for the “transition months” when the weather can fluctuate wildly have shown little reliability.

Watches and Warnings

The NWS issues *watches* and *warnings* to alert the public about potentially dangerous weather. A **watch** means that conditions are right for hazardous weather development and that residents should be aware and ready to act. A **warning** means that dangerous weather has already developed and has been observed in or is moving toward the designated area. For severe thunderstorms, tornadoes, and flash floods—events that develop quickly—response times are usually very short, so taking immediate shelter is strongly recommended. A hurricane warning means to either evacuate or move to a safe location.

> A watch means conditions are right for hazardous weather development, whereas a warning means that dangerous weather has developed and is moving toward the designated area.

The **Storm Prediction Center (SPC)** in Norman, Oklahoma, has the primary responsibility for forecasting severe weather such as thunderstorms, tornadoes, hail, and lighting. Whenever possible, "outlooks" for areas that might incur severe weather are issued a day prior to the anticipated event. The SPC then works with the local forecast offices of the NWS that are equipped with weather radar to monitor severe weather events as they develop. Before a warning is issued, the NWS wants to be relatively certain that a severe weather event has in fact developed. To aid in this process, a volunteer program called SKYWARN was created. Thousands of volunteers serve as spotters who provide critical information on the location and movement of the severe weather event. Once such an event is reported, the NWS broadcasts a warning via weather radio and contacts governmental authorities responsible for public safety in the affected areas.

Tracking and monitoring tropical storms and hurricanes in the Atlantic, Caribbean, and eastern Pacific is the task of the **National Hurricane Center (NHC)** in Miami, Florida. An important forecast challenge for the NHC is population growth along the Gulf and Atlantic coasts, with some areas requiring a 24-hour warning for evacuation. Additional evacuation time is also needed for people located on offshore or barrier islands that have limited access to the mainland.

Concept Checks 12.7

- How is a quantitative forecast different from a qualitative forecast?
- Explain the difference between a weather watch and a warning.
- What two weather elements are predicted on long-range (monthly) weather charts?

12.8 The Role of the Forecaster

LO 8 Describe how AWIPS and thermodynamic diagrams are used by local Weather Forecast Offices. List strategies for forecasting temperature and precipitation.

Despite faster computers, continual improvements in numerical models, and significant technological advances, numerical weather forecasts provide only a partial picture of atmospheric conditions for a specific region at any given time into the future. Human forecasters, using their knowledge of meteorology as well as judgments based on experience, continue to serve a vital role in creating weather forecasts, particularly short-range forecasts.

Forecasting Tools

The NWS provides a local forecaster with the observational data, satellite feeds, numerical model outputs, and the various weather maps discussed earlier in this chapter. Forecasters at the local Weather Forecast Offices are responsible for modifying numerical predictions by taking into account local conditions and nuances to produce site-specific forecasts. One local condition that forecasters must consider is the existence of microclimates—different climatic zones within a relatively small area. For example, Napa Valley, California, a prominent wine-producing district, is an area with a microclimate; the southern part of the valley is cooler than the northern part because of its close proximity to the cool waters of San Pablo Bay. This seemingly small difference is an important factor in growing grapes.

The task of forecasting is further complicated by the availability of multiple forecast outputs. For example, two different numerical models are generally employed to predict the minimum temperature for a given day. The forecaster must have a basic understanding of each model's biases and limitations in different forecasting situations before selecting the best output data. For example, forecasters may know that the first model tends to predict minimum temperatures for their forecast area that are a degree or two lower than the actual recorded value. Therefore, if the first model predicted a minimum temperature of 45°F and the second model predicted a minimum of 47°F, the forecaster should feel confident using 47°F as the forecast value. In other situations, when no model biases are known for predicting a particular weather element, the forecaster may choose to blend data from both models.

Advanced Weather Interactive Processing System

To aid in the enormous task of weather forecasting, local weather forecast offices are equipped with an interactive computer system called the **Advanced Weather Interactive Processing System (AWIPS)**. AWIPS is an information processing, display, and communication system that integrates all model and observational data, including satellite and radar data, in one location. An AWIPS workstation consists of three graphical displays and usually one or more personal computers for interacting with text materials (Figure 12.23). The three AWIPS graphic monitors are connected to a mainframe computer and can be configured into as many as 20 different windows—each displaying different weather information. Forecasters use this system to analyze and integrate the following types of data:

Figure 12.23 Advanced Weather Interactive Processing System (AWIPS)

AWIPS integrates all model and observational data, including satellite and radar data, in one location. An AWIPS workstation consists of three graphical displays and usually one or more personal computers for interacting with text materials.

- Numerical weather forecast products
- Doppler radar (the WSR-88D) displays, including dual-polarization radar
- GOES data
- Surface data from an Automated Surface Observing System (ASOS)
- Forecast guidance products from the National Hurricane Center and the Storm Protection Center
- Upper-air sounding data from radiosondes launched at nearby sites
- Surface weather maps and upper-level charts.

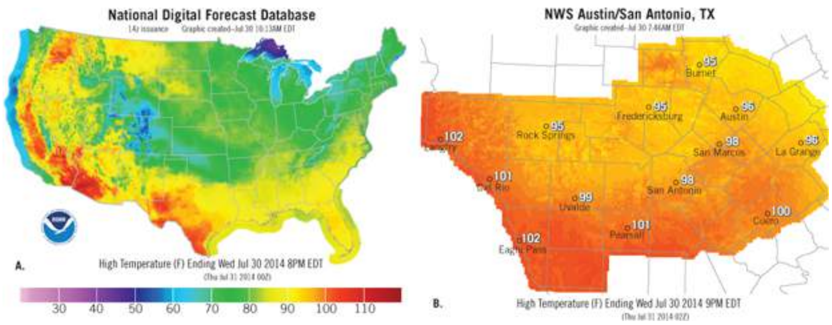
There are usually multiple AWIPS systems found in each local Weather Forecast Office.

> AWIPS is a tool used by forecasters that integrates all model and observational data, including satellite and radar data, in one location.

Once forecasters are confident in their modifications to the original guidance, the computer system automatically creates all the forecast products. In addition to a text forecast, the system produces an entire suite of forecast graphics, accessible via the Internet. Graphical forecasts for the entire United States, as well as regional and local forecasts for various weather elements, are available by searching online for "NWS graphical forecasts." Figure 12.24 includes a typical graphic produced for July 30, 2014, showing the predicted maximum daily temperatures for the entire United States and another showing temperatures for the Austin/San Antonio area of Texas.

Figure 12.24 Graphical forecast predicting maximum daily temperatures

A. This graphical forecast is for the entire continental United States on July 30, 2014. **B.** The predicted maximum daily temperatures for the Austin/San Antonio area of Texas on that same date.



Thermodynamic Diagrams

In addition to observational data described earlier, forecasters utilize diagrams on which the upper-level data (soundings) collected by radiosondes are plotted. These graphs, called **thermodynamic diagrams**, provide a vertical profile of the temperatures, dew-point temperatures, and wind through the atmosphere for a particular time and location. One of the most commonly used thermodynamic diagrams, called a **Skew-T/Log P diagram**, or simply a **Skew-T**, is described in Box 12.1. Although Skew-T diagrams look complicated, they are particularly useful for assessing the potential for *atmospheric instability*—a trigger for severe weather. (The Skew-T diagram is similar to the Stuve diagram described in Box 4.3.)

> Thermodynamic diagrams provide a vertical profile of the temperatures, dew-point temperatures, and wind through the atmosphere for a particular time and location.

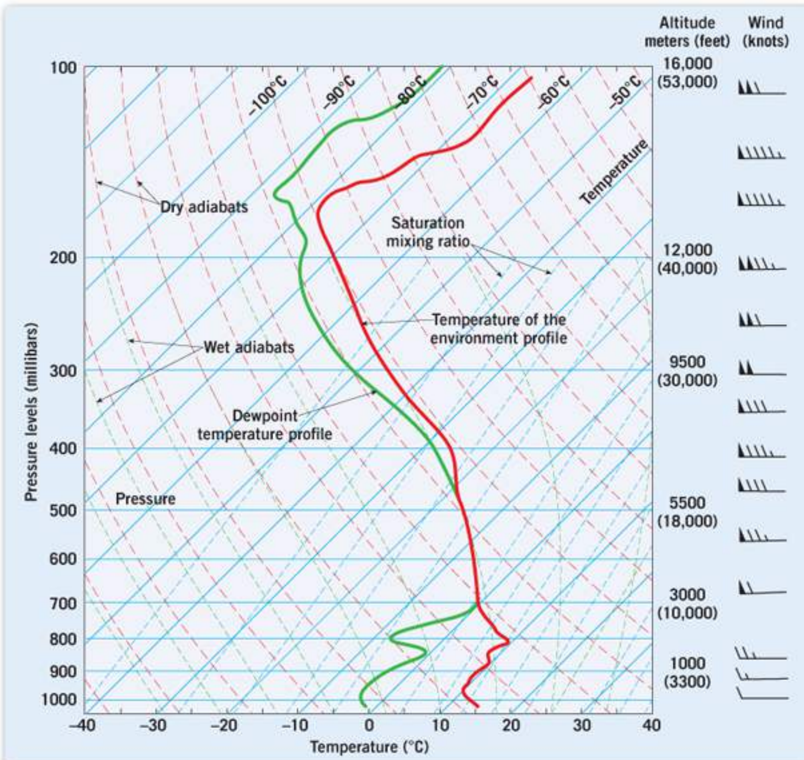
Box 12.1

Thermodynamic Diagrams

Forecasters display and analyze upper-air data (soundings) collected by radiosondes on *thermodynamic diagrams*. Such a graph provides a vertical profile of the temperatures and dew-point temperatures through the atmosphere for a specific time and place. Figure 12.A shows a thermodynamic diagram similar to that used by the NWS, called a *Skew-T/Log P diagram*, or simply a *Skew-T.* The horizontal blue lines represent *pressure levels* in 100-millibar (mb) increments along the left margin. Slanted (skewed) solid blue lines indicate *temperature* and are labeled every 10°C—hence the name *Skew-T*. The curved thin dashed red lines almost perpendicular to the temperature lines are the *dry adiabats*. Recall that the dry adiabatic rate is the rate that an unsaturated parcel of air will cool when forced to rise—about 10°C per 1000 meters. The thin dashed green lines are *wet adiabats*, which depict the rate at which a saturated parcel of air cools as it rises through the atmosphere. Saturation mixing ratios—the amount of water vapor required to saturate air at a given temperature—are shown with thin dashed blue lines. Wind speed and direction are also plotted along the right side of the diagram. One full bar represents 10 knots (about 1.15 miles per hour), and one triangle indicates 50 knots (57.5 miles per hour). Note how wind speed and direction change with height.

Figure 12.A **Thermodynamic diagrams**

Forecasters typically display and analyze upper-air data (soundings) collected by radiosondes on a type of thermodynamic diagram called a Skew-T/Log P diagram, or simply a Skew-T. Such a graph provides a vertical profile of air and dew-point temperatures through the atmosphere for a particular time and location.

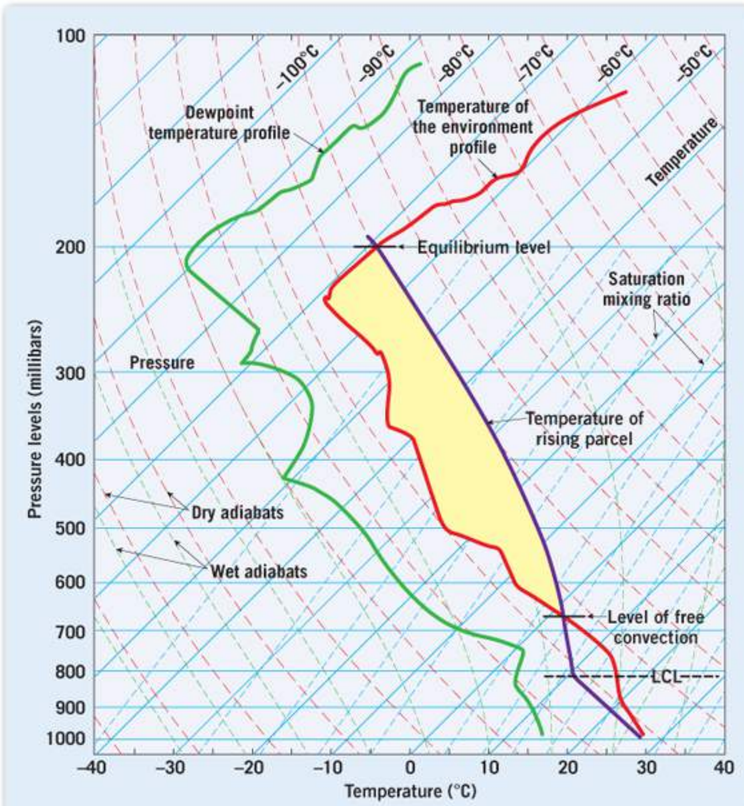


The two weather elements plotted on the Skew-T diagram in Figure 12.A are actual air temperatures (solid red line) and dew-point temperatures (solid green line) recorded by a radiosonde carried over Green Bay, Wisconsin. Thus, a Skew-T diagram produces a snapshot of the atmosphere from the surface to the 100-millibar level. Notice that the dew-point temperature line and the temperature line overlap from about the 700-millibar level up to slightly above the 500-millibar level, where they separate. Recall that when air temperature and the dew-point temperature are the same, the air is saturated and water vapor condenses, usually to form clouds. Thus, this sounding indicates the existence of a cloud deck over Green Bay in a band roughly between the 700- and 480-millibar levels.

Using Skew-T diagrams effectively requires some practice, but they help forecasters assess potential instability that can lead to deep atmospheric convection—a condition that may generate towering cumulonimbus clouds and severe weather. The term *deep* means convection (mainly upward air movement, but downdrafts are also an important component) that begins near Earth’s surface and extends to the top of the troposphere. Figure 12.B is a Skew-T on which hypothetical dew-point and temperature soundings are plotted. Using this data, we can assess the stability (or instability) of the atmosphere by locating where a parcel of rising air is warmer than the surrounding atmosphere. The parcel of air located near Earth’s surface has a temperature of 27°C (*remember, the temperature line is slanted*) and was forced aloft by the passage of a warm or cold front. The violet line representing the temperature of the rising parcel begins at the surface and continues upward, parallel to the red dashed lines, because the rising air is not saturated and therefore cools at the dry adiabatic rate.

Figure 12.B Using a Skew-T diagram

Skew-Ts are useful for assessing the potential for instability that can lead to deep atmospheric convection. The yellow area (between the temperature and dew-point temperature lines) represents the amount of energy available for a storm. Larger areas can mean stronger storms.



> Using Skew-T diagrams effectively requires some practice, but they help forecasters assess potential instability that can lead to the development of severe weather.

Just below the 800-millibar level, the violet line intersects the lifting condensation level—the altitude at which condensation and cloud formation begin—marked on the diagram as LCL. Above the LCL, the violet line now runs parallel to the dashed green lines (the wet adiabatic rate for saturated air). At about the 650-millibar level, the violet curve intersects and crosses the sounding temperature curve (red line).

Therefore, above the 650-millibar level, the rising air is now warmer (less dense) than the temperature of the surrounding air (environment), causing it to become unstable and rise because of its own buoyancy. This altitude is called the *level of free convection (LFC)*. The region of instability and free convection exists until the line representing the temperature of the rising air once again intersects with the sounding temperature (red line) at about the 200-millibar level. At this altitude, the temperature of the rising parcel is again equal to that of its surroundings, causing the parcel to lose its buoyancy. This level is called the *equilibrium level* (*EL*) and is theoretically the height of the thunderstorm. However, deep convection often results in overshooting cloud tops—clouds that rise beyond the equilibrium level.

We can conclude from Figure 12.B that this sounding indicates the potential for deep convection. If this potentially unstable air were forced to rise as it passed over a mountain, or were lifted along a frontal boundary, it could generate severe thunderstorms. This type of information is invaluable to weather forecasters.

Apply What You Know

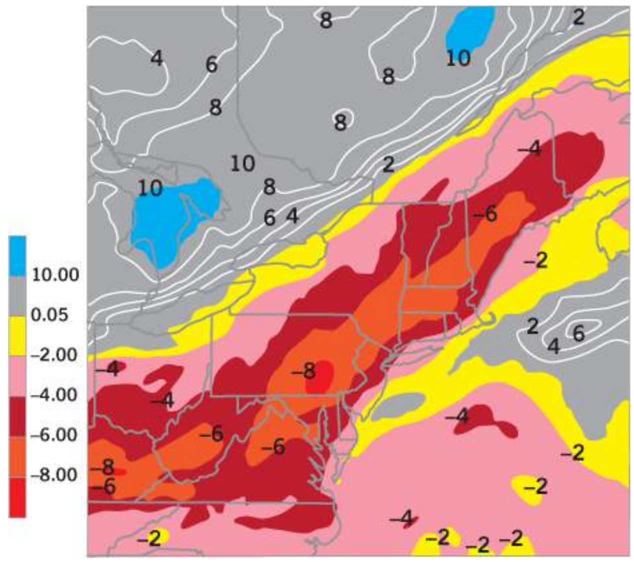
1. Between roughly what levels (in meters) of the atmosphere did the clouds located over Green Bay, Wisconsin, occupy? Based on their altitude, what was the cloud type?
2. Notice in Figure 12.A that temperatures generally decrease with height, except in the lower stratosphere. Locate the tropopause on this illustration.
3. Roughly how deep (in meters) is the zone of free convection shown in Figure 12.B?
4. What type of instability is illustrated in Figure 12.B?

There are other, less complicated, ways to determine the potential for instability in the atmosphere—two of these are the *K-index* and the *lifted index*. The K-index is used mainly to predict the occurrence of ordinary thunderstorms that produce heavy rainfall but not typically accompanied by severe weather. Thunderstorm potential, as measured by K-indices, is based on the environmental lapse rate, the moisture content of the lower atmosphere, and the vertical extent of the moist layer. K-indices are also used to determine the potential for flooding; a high K-index indicates a strong flooding potential.

By contrast, the *lifted index* is a number generated by hypothetically lifting a parcel of air from Earth's surface to the 500-millibar level, then comparing its temperature to that of the environment aloft. The *lower* the lifted index value, the *more unstable* the atmosphere is in that location (Figure 12.25). The lifted index can indicate the severity of potential thunderstorms.

Figure 12.25 **Lifted index**

The lower the lifted index value, the more unstable the atmosphere is at that location. Values of –4 or lower (represented by shades of red) denote unstable air with potential to produce severe thunderstorms. By contrast, values above 10 (shown in blue) are very stable.



Forecasting Using Rules of Thumb

A primary goal of a forecaster is to improve on the MOS forecasts, which are the baseline used by NWS forecasters. Recall that MOS forecasts are highly refined forecasting products built from the data generated from numerical forecast models. One way to accomplish this goal is by using simple rules of thumb to aid in forecasting the various weather elements.

Forecasting Temperature

Weather conditions that are quite simple to predict using model guidance are the maximum and minimum temperatures, which tend to occur in the midafternoon and early in the morning, respectively. When forecasting temperatures, meteorologists consider the following factors:

- **Extent of cloud cover** Overnight clouds absorb and reradiate longwave terrestrial radiation back to Earth's surface, making the day's minimum temperature higher than it would be on a cloud-free evening. Daytime clouds reduce surface heating and result in cooler-than-expected daytime high temperatures. Clear skies, by contrast, allow more solar radiation to reach Earth's surface, producing warmer-than-expected maximum temperatures.
- **Advection** A surface map can indicate the direction the wind is coming from (the upstream direction). Cold, dry air upstream usually results in colder-than-normal nights—in part because of the advection (horizontal flow) of cooler air and because clear skies promote radiation cooling. By contrast, the advection of warm, moist air will produce warmer-than-average nighttime temperatures. Advection aloft can be seen on upper-level charts and has a similar effect.
- **Snow cover** Because snow efficiently radiates longwave radiation, snow cover, especially when coupled with dry, clear air, can result in extremely cold nighttime temperatures.
- **Fronts** The passage of a warm or cold front greatly influences the timing and magnitude of the maximum and minimum temperatures for a particular day. Therefore, examining a series of surface maps can be useful in estimating the arrival of a front. A warm front arriving in the late afternoon on a cool day may cause the high to occur much later in the day—possibly just before midnight. By contrast, a cold front arriving in the morning could result in the maximum daily

temperature occurring just after midnight (before the cold front passes).

Forecasting Precipitation

Unlike temperature, precipitation can be particularly hard to predict. Factors to take into account when predicting precipitation include the following:

- **Low PoP and QPF** When the PoP (Probability of Precipitation) is less than 30 percent, precipitation is unlikely. Similarly, when the QPF (Quantitative Precipitation Forecast) is less than a quarter inch, the amount of precipitation predicted for an area is minimal. Stable conditions accompanied by low PoP and QPF readings make precipitation highly unlikely. However, if the air is unstable, as determined by examining thermodynamic diagrams (see Box 12.1), scattered or isolated thunderstorms are more likely.
- **Timing precipitation** Precipitation associated with a cold front usually occurs *with the passage* of the front, whereas precipitation associated with a warm front usually occurs *before its passage*. Weather radar is a tool for determining the rate at which precipitation along a front is approaching the forecast area and therefore helps predict the time that the precipitation will begin and end. Isolated summer thunderstorms are more likely to occur in the afternoon, when solar heating is most intense. Mountain and sea breezes also tend to occur during the warmest part of the day, affecting the timing of precipitation in mountainous and coastal areas.
- **Precipitation quantities** Precipitation amounts tend to be higher with slow-moving or stagnant fronts. Frontal precipitation is heavier in the late afternoon or evening, when solar heating has enhanced the instability of the air forced aloft. Dew-point temperature provides a clue to the water-vapor content of the air that will be forced aloft by a front: Very humid air can produce towering cumulonimbus clouds and torrential downpours if it is forced to rise.

Concept Checks 12.8

■ Explain AWIPS and briefly describe how it aids forecasters at local Weather Forecast Offices.

■ How are thermodynamic diagrams used to help forecasters?

■ Describe how cloud cover affects minimum and maximum temperature forecasts.

12.9 Forecast Accuracy

LO 9 Explain why the percentage of accurate forecasts is not always a good measure of forecast skill.

Forecast skill can be described as the improvement that a particular forecast method (or a forecaster) has over a standard forecast technique, such as *climatology*. One example of a climatology forecast would be to predict that the maximum temperature for Peoria, Illinois, on July 6, 2017, would be 86°F, based on historical averages of maximum temperature for that date and location. (*Note:* The actual maximum temperature for that date and location was 91°F.) A perfect forecast result compared to climatology would be given a forecast skill value of 1.0.

The percentage of accurate forecasts cannot be the only consideration for determining forecast skill. For example, measurable precipitation in Los Angeles is recorded only 11 days each year, on average. This means that, based on climatic data, the chance of rain in Los Angeles is 11 out of 365, or about 3 percent. Knowing this, a forecaster could predict no rain for every day of the year and be correct 97 percent of the time! Although the accuracy is high, the forecast would not indicate skill. For a method to exhibit forecasting skill, it must generate forecasts that are more accurate than those based simply on climatic averages. Using the Los Angeles example, a forecast method must be able to predict rain on at least a few of the days that rain actually occurred in order to demonstrate skill.

> For a method to exhibit forecasting skill, it must generate forecasts that are more accurate than those based simply on climatic averages.

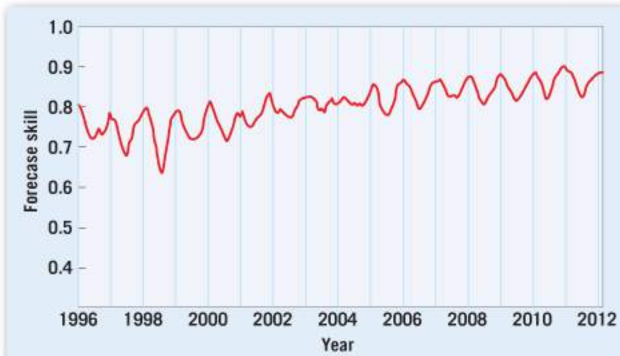
Although the occurrence of precipitation can be forecast with more than 80 percent accuracy, predictions of the amount, time of occurrence, and duration are not as reliable—particularly when the precipitation occurs in the summer in association with ordinary thunderstorms that cannot be predicted by current numerical models. A forecast might predict 2 inches of rain for an area, but one town might receive a trace, whereas a neighboring community may be deluged with 4 inches. By contrast, winter precipitation, especially snowfall amounts, can be forecast with much better accuracy. This is because winter precipitation tends occur more slowly and over wider areas that are closely associated with fronts and midlatitude cyclones.

How skillful are NWS weather forecasts? In general, very short-range forecasts (0–12 hours) have demonstrated considerable skill, especially for predicting the formation and movement of severe weather such as thunderstorms, hail, and heavy rainfall.

On average, a 5-day forecast using modern techniques is as reliable as a 2-day forecast was about 20 years ago. Figure 12.26 shows that over the past several years, the accuracy of 5-day forecasts at predicting airflow patterns aloft has improved significantly. The values closest to 1 on the graph represent higher skill. Figure 12.26 also shows the annual variability of forecast skill. Note that forecast accuracy is much higher in winter than during the midsummer months.

Figure 12.26 **Improvement in forecast skill**

The accuracy of 5-day forecasts at predicting airflow patterns aloft has improved significantly. When reading this graph, note that values closest to 1 represent higher skill. Note that forecast accuracy is much higher in winter than during the summer months.



Medium-range forecasts (3–7 days) have also shown significant improvement over the past decade. Yet beyond day 7, the predictability of day-to-day weather, even using these modern methods, proves only slightly more accurate than projections made from climatic data.

Several factors account for the limited range of modern forecasting techniques. As noted earlier, erroneous data and a network of observing stations that provides only limited coverage of our vast planet are significant hindrances. Not only are large areas of Earth's land–sea surface monitored inadequately, but also global data from the middle and upper troposphere are meager. Moreover, the physical laws of nature are difficult to apply to chaotic systems such as Earth's atmosphere, and current numerical models cannot adequately account for the vast number of atmospheric variables.

The accuracy of weather forecasts covering short- and medium-range periods has improved steadily over the past few decades, particularly in forecasting the evolution and movement of midlatitude cyclones.

Technological developments, improved computer models, and a better understanding of how the atmosphere behaves have added greatly to this success. The ability to accurately predict daily weather beyond day 7, however, remains relatively low.

> The accuracy of weather forecasts covering short- and medium-range periods has improved steadily over the past few decades.

Concept Checks 12.9

■ What is meant by *forecast skill*? Give an example of why the percentage of correct forecasts is not always a good measure of forecast skill.

■ Which weather element is forecast as a percentage probability?

■ List two reasons why modern forecasting techniques do not accurately predict the weather beyond 7 days for most regions of the United States.

Concepts in Review

12.1 The Weather Business: A Brief Overview

LO 1 List and describe the major steps used to generate a weather forecast.

Key Terms

National Weather Service (NWS)

weather forecast

National Centers for Environmental Prediction (NCEP)

Canadian Meteorological Centre

Weather Forecast Offices (WFO)

meteorologist

- The U.S. government agency responsible for gathering and disseminating weather-related information is the National Weather Service (NWS). Perhaps the most important services provided by the NWS are forecasts and warnings of hazardous weather.
- The process of providing weather forecasts and warnings throughout the United States occurs in three stages. First, observational data are collected and analyzed on a global scale. Second, a variety of techniques are used to establish the future state of the atmosphere—a process called weather forecasting. Finally, forecasts are disseminated to the public, mainly through the private sector.

NOAA

12.2 Acquiring Weather Data

LO 2 Describe the various tools used to acquire weather data.

Key Terms

World Meteorological Organization (WMO)

Automated Surface Observing Systems (ASOS)

radiosonde

atmospheric sounding (sounding)

- On a global scale, the World Meteorological Organization (WMO) is responsible for gathering, plotting, and distributing weather data.
- Automated Surface Observing Systems (ASOS) are modern automated systems that provide weather observations such as temperature, dew point, wind speed and direction, visibility, cloud cover, and precipitation type and amount.
- Radiosondes carried aloft by weather balloons contain sensors that measure temperature, humidity, and pressure. Much of the upper-level data used to prepare upper-level weather charts comes from these instrument packages.

NOAA

12.3 Weather Maps: Depictions of the Atmosphere

LO 3 Interpret what a particular pattern in the flow aloft indicates about surface weather.

Key Terms

weather analysis

surface weather analysis (surface analysis)

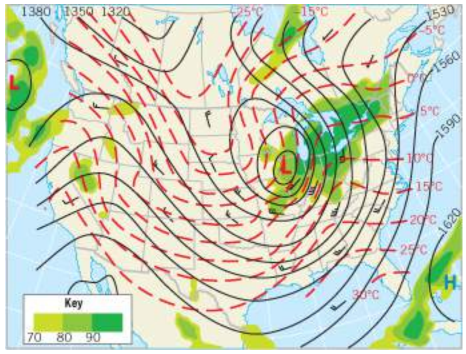
isotach

jet streak

zonal

meridional

- Assessing current atmospheric conditions, called weather analysis, involves collecting, compiling, and transmitting billions of pieces of observational data.
- Surface weather maps that include the locations of pressure systems and fronts are called surface weather analysis (or simply, surface analysis). These maps organize and display vast amounts of surface data so that users can discern large-scale weather patterns.
- Upper-air maps are generated twice daily and provide forecasters with a picture of conditions at various levels in the troposphere. These maps are used to predict daily maximum temperature, locate areas where precipitation is likely to occur, and determine whether a thunderstorm will produce a severe weather event.



1380
1350
1320
-25°C
-15°C
1530
-5°C
0°C
1560
5°C
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1620
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70
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90

12.4 Modern Weather Forecasting

LO 4 Explain the basis of numerical weather prediction.

Key Terms

numerical weather prediction

forecast model

Model Output Statistics (MOS)

prognostic chart (prog)

ensemble forecasting

- Numerical weather prediction relies on the fact that the behavior of atmospheric gases is governed by a set of physical principles or laws that can be expressed as mathematical equations.
- A statistical analysis called Model Output Statistics (MOS) is used to modify and correct these machine-generated forecasts by making comparisons of how accurate previous forecasts have been.
- Ensemble forecasting involves producing a number of forecasts using the same computer model but slightly altering the initial conditions to assess uncertainty.

NOAA

12.5 Other Forecasting Methods

LO 5 Distinguish among the various traditional methods of weather forecasting.

Key Terms

persistence forecasting

climatological forecasting

analog method

trend forecasting

nowcasting

- Methods used in addition to numerical weather prediction include persistence forecasting, climatological forecasting, the analog method, and trend forecasting. A type of trend forecasting called nowcasting is used to forecast very short-lived (usually 6 hours), localized weather events.

12.6 Weather Satellites: Tools in Forecasting

LO 6 Discuss the advantages and disadvantages of infrared, visible, and water-vapor imagery generated by weather satellites.

Key Terms

Polar-orbiting Operational Environmental Satellite (POES)

Geostationary Operational Environmental Satellite (GOES)

- Polar-orbiting satellites (POES) and geostationary satellites (GOES) are important tools that allow meteorologists to monitor even the most remote parts of the globe and track the movement of large weather systems.
- These satellites provide visible, infrared, and water-vapor images that are useful in the study of clouds and the distribution of water vapor.
- Visible imagery provides information about cloud thickness, and infrared imagery provides information about cloud height.

12.7 Types of Forecasts

LO 7 Compare and contrast qualitative and quantitative weather forecasts. Differentiate between weather forecasts and 30- and 90-day outlooks.

Key Terms

qualitative forecast

quantitative forecast

Quantitative Precipitation Forecast (QPF)

Probability of Precipitation (PoP)

Climate Prediction Center (CPC)

watch

warning

Storm Prediction Center (SPC)

National Hurricane Center (NHC)

- Qualitative forecasts describe an aspect of the weather that can be observed but not easily measured or quantified, while quantitative forecasts deal with weather data that can be measured, such as maximum and minimum temperatures.
- The only forecast issued by the NWS that is given as a percentage probability is precipitation.
- Long-range weather forecasting relies heavily on statistical averages obtained from past weather events, known as climatic data. Weekly, monthly, and seasonal weather outlooks prepared by the NWS are not weather forecasts in the usual sense but indicate whether a region will experience near-normal precipitation and temperatures.
- A watch means conditions are right for the development of dangerous weather. A warning means that dangerous weather has developed and has been located in or moving toward an area.


Equal
chances
Warmer
Warmer
Equal
chances

12.8 The Role of the Forecaster

LO 8 Describe how AWIPS and thermodynamic diagrams are used by local Weather Forecast Offices. List strategies for forecasting temperature and precipitation.

Key Terms

Advanced Weather Interactive Processing System (AWIPS)
thermodynamic diagram
Skew-T/Log P diagram (Skew-T)

- The job of issuing local weather forecasts, watches, and warnings rests with the National Weather Service (NWS) and its 122 local Weather Forecast Offices. Forecasters at the Weather Forecast Offices modify numerical predictions by considering local conditions and nuances to produce site-specific forecasts.
- The Advanced Weather Interactive Processing System (AWIPS) is an informational processing, display, and communication system that integrates all model and observational data, including satellite and radar data, in one location.
- The NWS utilizes a thermodynamic diagram called a Skew-T/Log P diagram, or simply a Skew-T, on which temperature and dew-point data from the surface through the top of the troposphere is plotted. These diagrams, along with the lifted index and the K-index, are useful for determining the potential instability of the atmosphere.
- A primary goal of a forecaster is to try to improve on MOS forecasts. One way to accomplish this goal is by utilizing some rules of thumb.

12.9 Forecast Accuracy

LO 9 Explain why the percentage of accurate forecasts is not always a good measure of forecast skill.

Key Terms

forecast skill

- Over the past several decades, improvements in observing systems, computer models of physical processes, and assimilation of data into numerical weather prediction systems have steadily improved the ability to predict the evolution of larger-scale weather systems as well as day-to-day variations in temperature, precipitation, and the extent of cloud cover.

Exercises and Online Activities

Mastering Meteorology™

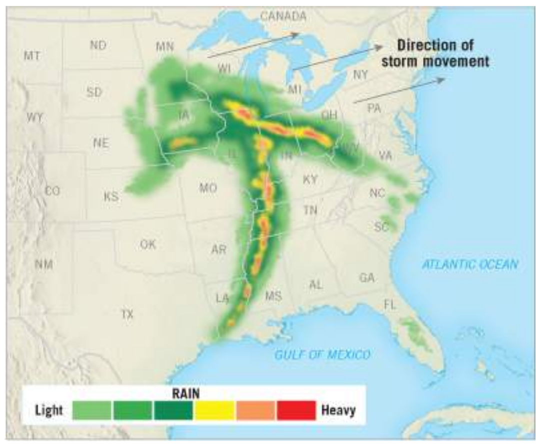
For instructor-assigned homework, test prep resources, and other learning materials, visit **Mastering Meteorology.**

Review Questions

1. **1.** Which U.S. government agency is responsible for disseminating weather-related information?
2. **2.** Approximately what percentage of all declared emergencies is weather related?
3. **3.** Describe the role that a forecaster plays in creating a forecast.
4. **4.** What is an ASOS?
5. **5.** How are most weather data aloft gathered?
6. **6.** What are the goals of weather analysis?
7. **7.** Explain the connections between surface weather maps and upper-air charts.
8. **8.** Define *isobar*, *isotherm*, and *isotach*.
9. **9.** How does knowing the position of the jet stream aid in forecasting severe weather?
10. **10.** Briefly explain how a numerical weather prediction is generated.
11. **11.** How is an ensemble forecast created, and why is it useful?
12. **12.** What assumptions are made for persistence forecasting? Climatological forecasting? Analog forecasting? Trend forecasting?
13. **13.** Compare and contrast visible, infrared, and water-vapor satellite imagery.
14. **14.** What is meant by a 50 percent chance of rain over an area?
15. **15.** How much time does a short-range forecast cover? A medium-range forecast?
16. **16.** What is a long-range outlook? Which agency issues these?
17. **17.** What is AWIPS?
18. **18.** What is a Skew-T diagram, and why is it useful?
19. **19.** Describe four rules of thumb for forecasting *temperature*.
20. **20.** List three rules of thumb for forecasting *precipitation*.
21. **21.** How is forecast skill determined? Is it the same as forecast accuracy?

Give It Some Thought

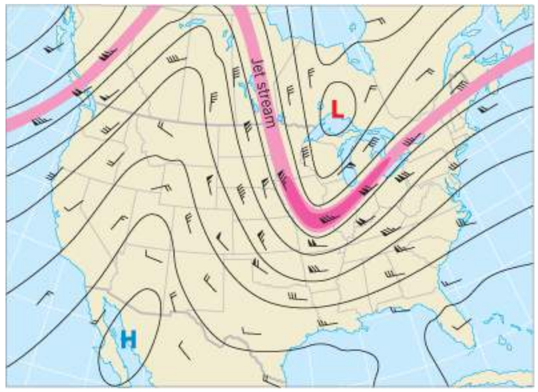
1. The accompanying radar image shows the precipitation pattern (reds and yellow indicate heavy precipitation, and greens indicate light-to-moderate precipitation) associated with a strong midlatitude cyclone. Use the technique called trend forecasting, and assume that the cyclone maintains its current strength for the next 24 hours as you complete the following.



   a. What state(s) will likely experience thunderstorms associated with a cold front in the next 6 to 12 hours?
   b. Will the temperatures in Alabama more likely rise or fall during the next 24 hours? Explain.
   c. Will Pennsylvania more likely be warmer or colder in 24 hours than it was when the image was produced? Explain.
   d. In which state, New York or Georgia, would cirrus clouds more likely have been overhead when the image was produced?

2. The accompanying map is a simplified upper-air chart showing flow aloft and the position of the jet stream. Weather patterns such as this are relatively common over North America. When answering the following questions, assume that long-range

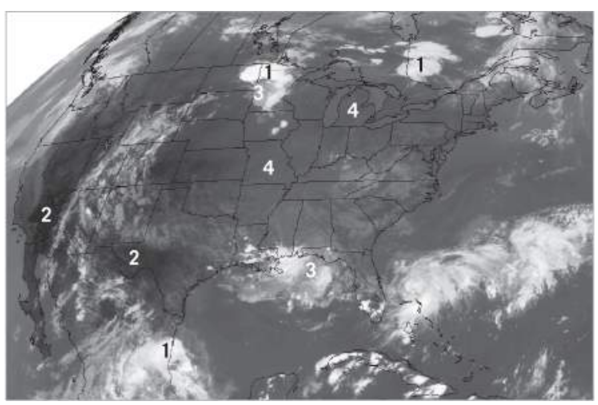
weather forecasters had evidence that this flow pattern was going to persist for several months.



a. Would the 90-day outlook for the southeastern United States predict wetter-than-normal, drier-than-normal, or equal chance? Explain your answer.

b. Would the 90-day outlook for the southwestern United States predict wetter-than-normal, drier-than-normal, or equal chance? Explain your answer.

3. The accompanying infrared satellite image shows a portion of North America at midday. Match the numbers on the image to descriptions a–d.



a. These areas are cloud free, and the infrared sensor is measuring very warm surface temperatures.

b. These areas contain low clouds (cumulus), with cloud tops below 2000 meters.

c. These areas are blanketed by middle clouds between 2000 and 6000 meters.

d. These are areas where the infrared sensor is measuring high, cold cloud tops that are likely associated with towering cumulonimbus clouds and thunderstorms.

4. Sketch a hypothetical orbit for a polar-orbiting and a geostationary satellite on the same diagram (two orbits around Earth). Make sure the orbits are drawn to indicate relative height above Earth's surface.
   a. List one advantage of a polar-orbiting satellite.
   b. List one advantage of a geostationary satellite.
   c. Explain why geostationary satellites orbit at about 36,000 kilometers (22,000 miles) above Earth's surface.

5. The accompanying maps show the positions of the jet stream on two different midwinter days. On which of these days would the southeastern United States be warmer? Explain your choice.

By the Numbers

1. Determine the probability of precipitation (PoP) using the formula below and the following information:

$$\text{PoP} = (C \times A) \times 100\,\text{percent}$$

where *C* is the *confidence* that precipitation will occur *somewhere* in the forecast area, and *A* equals the *percentage of the area* that will receive measureable precipitation if it occurs.

   a. A forecaster expresses confidence that there is an 80 percent chance of precipitation in the forecast area, and it is expected to produce measurable precipitation over 90 percent of the area.

   b. A forecaster expresses confidence that there is a 20 percent chance of precipitation in the forecast area, and it is expected to produce measurable precipitation over 10 percent of the area.

2. Many weather reports include a 7-day outlook. Check such a report and jot down the forecast for the last (7th) day. Then, each day thereafter, write down the forecast for the day in question. Finally, record what actually occurred on that day. Contrast the forecast that was generated 7 days ahead with what actually occurred. Describe in your own words how accurate (or inaccurate) the 7-day forecast was for the day you selected. How accurate was the 5-day forecast for that day? The 2-day forecast?

Beyond the Textbook

Weather Forecasting

This activity explores two sets of forecast maps produced for the same time period using two different computer models. Consider the following statements as you complete this activity: (1) Low-pressure systems (midlatitude cyclones) are associated with fronts. (2) Fronts lift moist air to cause clouds and precipitation. (3) "Mother Nature doesn't necessarily follow rules!"

1. Using the RAP Model

Go to http://www.rap.ucar.edu/weather/model/, then click on "Current analysis" under Quick-look charts on the right side of the page to show the current weather. On that map select a low "L" that has fronts associated with it. Then click on each of the other forecast maps and observe how that low is predicted to move and change.

1. Briefly describe the general movement of the low you selected.
2. Characterize the precipitation associated with this low. Did it intensify or diminish over the 48-hour forecast period?
3. Evaluate the forecast in terms of statements 1 and 2 above. Does the forecast support statements 1 and 2, or are they closer to statement 3? Justify your answer.

2. Using the WPC Model

Go to http://www.wpc.ncep.noaa.gov/basicwx/basicwx_ndfd.php and scroll over the day/time at the top left of the map to see the current weather conditions. On this map find the same low "L" you examined in Part A. Next, slowly scroll over the suite of maps (across the days/times from left to right) to see how that low is predicted to evolve.

1. Briefly describe the general movement of the low you selected.
2. Characterize the precipitation associated with this low (see precipitation key in the lower left corner of the map). Did it intensify or diminish over the 48-hour forecast period?
3. Evaluate the forecast in terms of statements 1 and 2 above. Does the forecast support statements 1 and 2, or are they closer to statement 3? Justify your answer.

3. Forecast for Your Location

Find your approximate location on each of the maps in Parts A and B.

1. Briefly describe how your weather forecast is likely to change over the next 48 hours for each forecast.
2. Do both models agree? If not, explain why.

Chapter 13 Air Pollution

India is plagued by air quality issues. Major contributors are coal-burning power plants. Heavy smog in November 2016 resulted in a week-long health emergency in New Delhi.

Focus on Concepts

Each statement represents the primary learning objective for the corresponding major heading within the chapter. After you complete the chapter, you should be able to:

1. Name several natural sources of air pollution and identify those that are enhanced by human activity (13.1).
2. List the six major pollutants monitored by the Environmental Protection Agency (EPA) and discuss their effects on people and the environment (13.2).
3. Summarize trends in air quality since 1980 (13.3).
4. Describe the influence of wind on air quality. Sketch a diagram showing a temperature inversion, and explain how it affects mixing depths (13.4).
5. Discuss the formation of acid precipitation and list some of its effects on the environment (13.5).

Breathing polluted air causes tens of thousands of premature deaths, increases the number of heart attacks, results in hundreds of thousands of asthma attacks in children, and costs millions of lost work days. Air pollution and meteorology are linked in two ways. First, weather conditions play a major role in concentrating, diluting, and dispersing air pollutants. Second, air pollution can affect weather and climate through the absorption and scattering of sunlight. The ways in which weather influences the distribution and severity of air pollution is examined in this chapter. The second and equally important relationship, how pollution alters weather and climate, is discussed in the following chapter.

13.1 The Air Pollution Threat

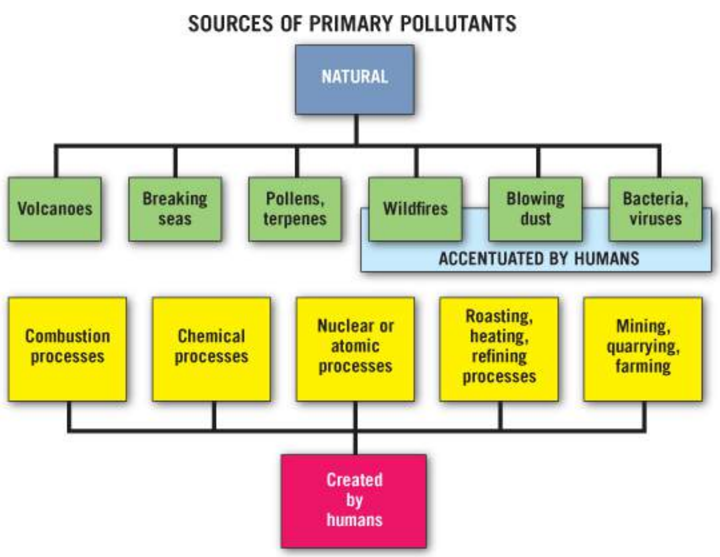
LO 1 Name several natural sources of air pollution and identify those that are enhanced by human activity.

Air pollution is a continuing threat to our health and welfare. According to a National Research Council report, people living in the most polluted cities in the United States lose an estimated 1.8 to 3.1 years of life because of chronic exposure to particulate matter. In addition, the World Health Organization (WHO) estimates that particulate matter (PM) contributes to approximately 800,000 premature deaths each year, ranking it the 13th leading cause of mortality worldwide. Air pollutants also have a negative impact on crop production, costing U.S. agriculture more than $10 billion annually. In newly industrialized countries such as China, India, and Brazil, the negative impact of air pollution on life and agriculture is even more serious.

Natural and Human-Accentuated Pollution

Air is never perfectly clean. Many natural sources of air pollution have always existed (Figure 13.1). Ash and gases from volcanic eruptions, salt particles from breaking waves, pollen and spores released by plants, smoke from forest fires, and windblown dust are all examples of "natural air pollution." As long as humans have occupied Earth, however, we have added to the frequency and intensity of some of these natural pollutants. For example, dust storms can occur when strong winds lift and transport dry soil from plowed farm fields.

Figure 13.1 Sources of primary pollutants



> Air has never been perfectly clean because there are many natural sources of air pollution.

The discovery of fire brought an increased number of accidental as well as intentional burnings (Figure 13.2). Even today, in many parts of the world, fire is used to clear land for agricultural purposes (slash-and-burn method), filling the air with smoke and reducing visibility. When land is cleared of its natural vegetative cover for any purpose, soil is exposed and blown into the air. Yet when we consider the air in a modern-day industrial city, these human-accentuated forms of pollution, although significant, seem minor by comparison.

Figure 13.2 Natural source of air pollution

Fire rages though southern California, August 17, 2016.

Pollution Created by Humans

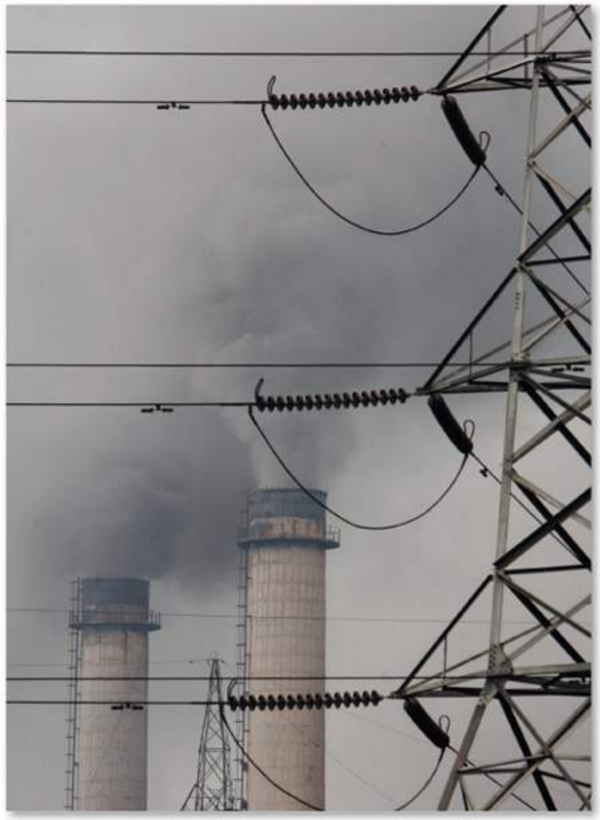
Although some types of air pollution are relatively recent creations, others have existed for centuries. In 1661, John Evelyn wrote about air pollution in London—specifically, the burning of sulfur-rich coal, which produced a terrible smell that plagued the city. In his book, Evelyn noted that a traveler, although many miles from London, "sooner smells than sees the city." In fact, London continued to have severe air pollution problems well into the twentieth century. It was only after a devastating smog disaster in 1952 that truly decisive action was taken to clean London's air.

London, however, did not have a monopoly on air pollution; with the coming of the Industrial Revolution many cities were plagued with dirty air. In addition to accelerating natural sources of pollution, people found new ways to pollute the air (see Figure 13.1) and many new things with which to pollute it. In the mid- to late nineteenth century, the populations of many American and European cities swelled as people sought work in the growing numbers of foundries and steel mills. As a result, the urban environment became increasingly fouled by the fumes of industry.

It should be noted that the rapid rise in urban air pollution was not always viewed with great alarm. Rather, chimneys belching forth smoke and soot were a symbol of growth and prosperity (Figure 13.3). A well-known orator, Robert Ingersoll, is reported to have elicited great cheering and cries of "Good! Good!" from the audience for this statement in an 1880 speech: "I want the sky to be filled with the smoke of American industry and upon that cloud of smoke will rest forever the bow of perpetual promise." With rapid population growth and accelerated industrialization, the quantity of atmospheric pollutants increased drastically.

Figure 13.3 People influence the atmosphere

Stacks belching smoke and soot from a coal-fired electricity-generating plant in New Delhi, India.



Eye on the Atmosphere 13.1

This satellite image from NASA's *Landsat 8* satellite shows a portion of the Kenai Peninsula south of Anchorage, Alaska, on May 20, 2014. Dingy, gray smoke from several major wildfires pollutes the air. The well-developed cumulonimbus clouds present also owe their origin to the wildfires.

Apply What You Know

1. According to Figure 13.1, wildfires are a natural source of primary pollutants. This fact implies that the smoke in this image is a "natural pollutant." However, these fires had a human origin. Is this air pollution "natural"? What term or phrase best fits this example?
2. How could the wildfires have been responsible for the development of cumulonimbus clouds?

Since the 1970s, the passage of legislation, development of regulations and standards, and advances in technology have greatly reduced the frequency and severity of air pollution episodes in the United States and Western Europe. Nevertheless, health authorities remain concerned about the long-term impact of pollutants on human health and the environment. More recently, as less-developed countries have begun to modernize, this problem has dramatically expanded around the globe. According to the WHO, 13 of the 20 most polluted cities in the world today are in rapidly industrializing India.

> Although the number and severity of air pollution episodes have been greatly reduced, health authorities remain concerned about the long-term impact of pollutants.

You might have wondered . . .

What is haze?

Haze is a reduction in visibility caused when light encounters atmospheric particulate matter and gases. Before light reaches an observer, some is absorbed by the particles and gases, while some is scattered. More pollutants mean more absorption and scattering of light, which limit the distance we can see and can also degrade the color, clarity, and contrast of what we can see. Impaired visibility is one of the most obvious effects of air pollution.

Concept Checks 13.1

- Describe the impact of air pollution on human health.
- List several examples of natural air pollution. List three that are human accentuated.

13.2 Sources and Types of Air Pollution

LO 2 List the six major pollutants monitored by the Environmental Protection Agency (EPA) and discuss their effects on people and the environment.

Air pollutants are airborne substances (gases, solids, or liquids) that occur in concentrations that endanger the health and well-being of organisms and foul the environment. These suspended pollutants are called **aerosols** when they are sufficiently large that we notice their presence as they scatter or absorb sunlight. In addition to causing health problems, air pollution is the major cause of reduced visibility in many parts of the United States. These airborne materials can also damage paints and building materials, as well as harm vegetation, including croplands.

Pollutants can be grouped into two categories: primary and secondary. **Primary pollutants** are emitted directly from identifiable sources. They include particulate matter, sulfur dioxide, and nitrogen oxides, which pollute the air immediately upon being emitted. In contrast, **secondary pollutants** are produced in the atmosphere when certain chemical reactions occur that alter primary pollutants. Secondary pollutants include sulfuric acid and the chemicals that make up smog, such as ozone and nitric acid.

In the United States, the Clean Air Act requires the Environmental Protection Agency (EPA) to set air quality standards for six major air pollutants—known as *criteria air pollutants*. The criteria air pollutants include particulate matter (PM), sulfur dioxide (SO_2), nitrogen oxides

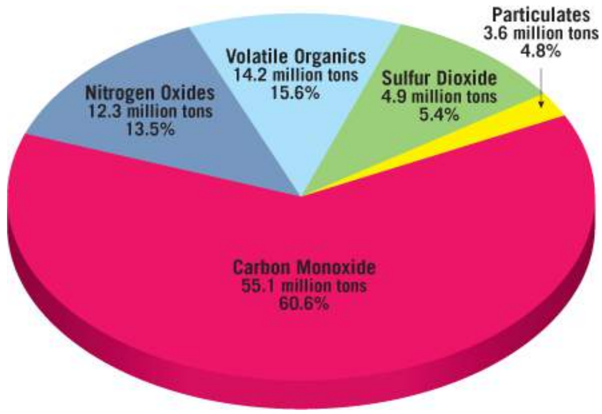
(NO_x), carbon monoxide (CO), lead (Pb), and ground-level ozone (O_3). Except for ozone, a secondary pollutant, all of the others are *primary* pollutants—meaning they are emitted directly from identifiable sources. Ozone, which forms from primary pollutants through various chemical reactions in the presence of sunlight, is discussed with photochemical smog later in the chapter. Other compounds that are not list as a criteria air pollutants by the EPA, but are none-the-less significant, are called volatile organic compounds (VOCs).

Major Primary Pollutants

Figure 13.4 depicts the major primary pollutants as percentages by weight. Sources vary for each pollutant. For example, electricity generation is the most significant source of sulfur dioxide. By contrast, on-road vehicles are the number-one source of carbon monoxide, nitrogen oxides, and volatile organic compounds. Compared to other sources, the tens of millions of cars and trucks on our streets and highways are clearly the greatest contributors.

Figure 13.4 Emissions estimates of primary pollutants for the United States in 2015

Percentages are calculated on the basis of weight. The total weight in 2015 was about 91 million tons.



> The six major air pollutants monitored by the EPA include particulate matter (PM), sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), lead (Pb), and ground-level ozone.

Particulate Matter

Particulate matter (PM) is the general term used for the mixture of tiny solid particles and liquid droplets suspended in the air. Particulates are frequently the most obvious form of air pollution because they reduce visibility (Figure 13.5) and leave deposits on the surfaces with which they come in contact. In addition, particulates may transport other pollutants dissolved in or absorbed on their surfaces. Most particulate matter is emitted directly from their sources, such as factories and cars. However, in other cases, gases such as sulfur dioxide react chemically with other compounds in the air to form fine solid or liquid particles, which makes them secondary pollutants.

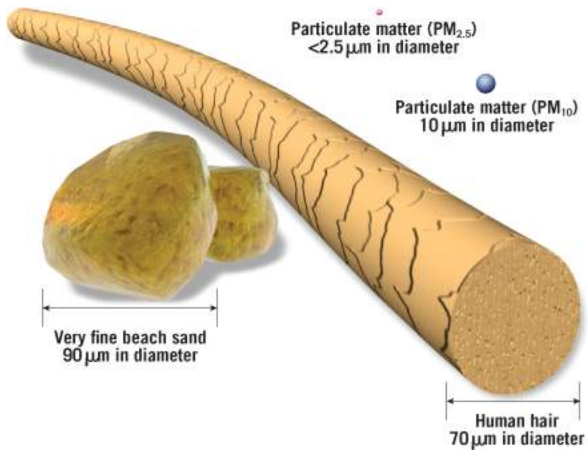
Figure 13.5 Air pollution episode in Shanghai, China

Coal-burning plants produce large amounts of particulate matter that reduce visibility.

Some particles are large or dark enough to be seen as dust, soot, or smoke; others can be detected only with an electron microscope (Figure 13.6). Fine particles ($PM_{2.5}$) are less than 2.5 micrometers in diameter, which is about 30 times smaller in diameter than a human hair. Most fine particles result from fuel combustion by motor vehicles, power generation, and industrial facilities, as well as from residential fireplaces and woodstoves. PM2.5 is especially dangerous to human health because it stays in the air longer and penetrates deep into the lungs.

Figure 13.6 Particulate matter (PM)

This category is a complex mixture of extremely small particles and liquid droplets. PM_{10} stands for "inhalable coarse particles," which are larger than 2.5 micrometers and smaller than 10 micrometers. $PM_{2.5}$ stands for "fine particles," which are 2.5 micrometers and smaller.



> Particulate matter (PM) is the general term used for a mixture of tiny, solid particles and liquid droplets found in the air.

Coarser particles (PM_{10}) are characterized as inhalable particles, with diameters between 10 and 2.5 micrometers (Figure 13.6). PM_{10} are emitted from sources such as mining operations, road construction, and windblown dust. The EPA monitors both 2.5- and 10-micron sized particles.

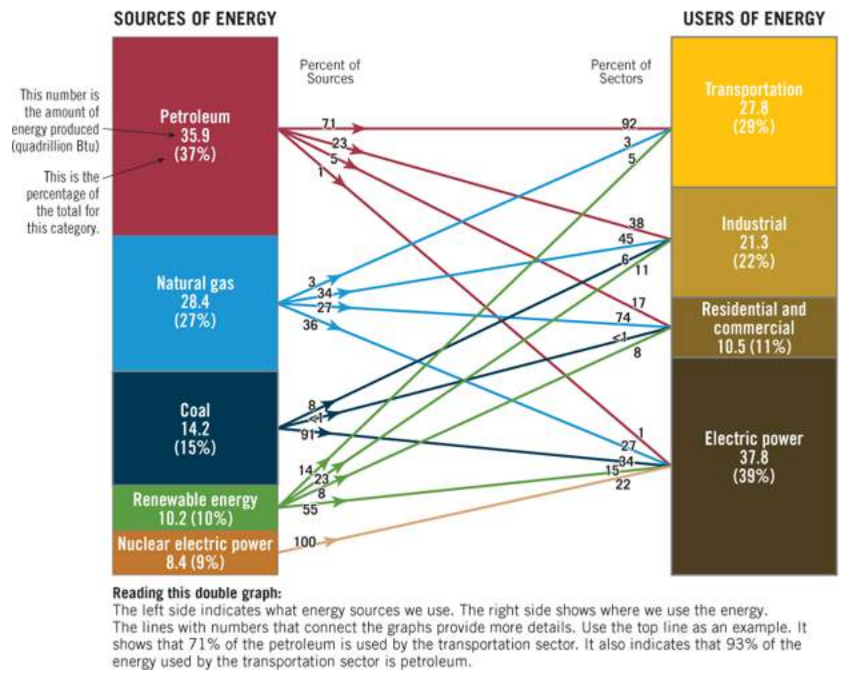
Inhalable particulate matter includes both fine and coarse particles. These particles can accumulate in the respiratory system and are associated with numerous health effects. Exposure to coarse particles is primarily associated with the aggravation of respiratory conditions, such as asthma. Fine particles, however, are most closely associated with increased respiratory symptoms, decreased lung function, and even premature death. Groups that are at greatest risk include elderly people, children, and individuals with cardiopulmonary disease.

Sulfur Dioxide

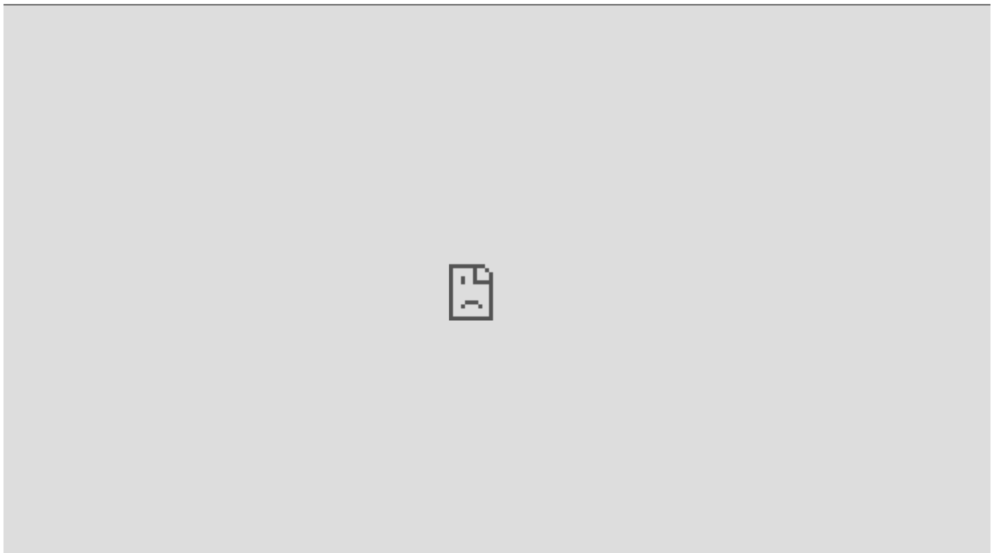
Sulfur dioxide (SO_2) is a colorless invisible gas that has a putrid, sharp smell. About 99 percent of sulfur dioxide comes from human sources—largely the combustion of sulfur-containing fuels, such as coal and oil (Figure 13.7). Major sources include power plants, smelters, petroleum refineries, and pulp and paper mills. Most of the remainder comes from gases emitted during volcanic eruptions.

Smartfigure 13.7 **U.S. energy consumption, 2015**

Total consumption was 97.7 quadrillion Btu. A quadrillion is 10 raised to the 12th power, or a million million.



Watch **SmartFigure: U.S. Energy Consumption**



For asthmatic individuals, short-term exposure to elevated SO_2 levels can reduce lung function and may be accompanied by such symptoms as wheezing, chest tightness, or shortness of breath. Other effects associated with longer-term exposure to high concentrations of SO_2 include respiratory illness and aggravation of existing cardiovascular disease, including heart failure and arrhythmia.

Once in the air, SO_2 usually reacts with water droplets or other substances to form sulfuric acid (H_2SO_4) and/or minute sulfate particles. These tiny acidic droplets and solid particles can be carried over long distances in the atmosphere. When it is “washed out” of the air or deposited on surfaces, sulfuric acid contributes to a serious environmental problem known as *acid precipitation*—an issue covered later in the chapter.

You might have wondered . . .

Burning of coal is considered a significant source of SO_2, but do we burn very much coal anymore?

We do. About 34 percent of the electricity produced in the United States comes from coal combustion (see Figure 13.7). Coal is also the fuel of choice for many heat-intensive processes, such as producing steel, aluminum, concrete, and wallboard. Many other countries are even more reliant on coal for their energy needs than the United States.

Nitrogen Dioxide

The EPA uses nitrogen dioxide (NO_2) as a measure of the presence of a family of highly reactive gases called *nitrogen oxides (NO_x).* Other nitrogen oxides include nitric oxide and nitric acid. Nitrogen oxides get in the air through the high-temperature combustion of fuel, when nitrogen in the fuel or the air reacts with oxygen.

Motor vehicles and power plants are the primary sources of nitrogen dioxide. Although NO_2 also forms naturally, its concentration in cities is 10 to 100 times higher than in rural areas. Nitrogen dioxide has a distinctive reddish-brown color that frequently tints polluted city air and reduces visibility. When concentrations are high, NO_2 can also contribute to lung and heart problems. When air is humid, NO_2 reacts with water vapor to form nitric acid (HNO_3). Like sulfuric acid, this corrosive substance also contributes to the acid rain problem. Moreover, because nitrogen oxides are highly reactive gases, they play an important part in the formation of smog.

Volatile Organic Compounds

Volatile organic compounds (VOCs), also called *hydrocarbons*, encompass a wide array of solid, liquid, and gaseous substances. (*Volatile* materials evaporate easily to become vapors or gases.) Large quantities of VOCs occur naturally, with methane (CH_4) being the most abundant. Methane does not interact chemically with other substances and has no negative health effects, but it does contribute to climate change and is discussed in more detail in the next chapter.

In cities, the incomplete combustion of gasoline in motor vehicles is the principal source of reactive VOCs. Although some hydrocarbons are cancer-causing agents, most of the VOCs in city air do not, by themselves, appear to pose significant environmental problems. However, when VOCs react with nitrogen oxides, the result is noxious secondary pollutants and smog.

Carbon Monoxide

Carbon monoxide (CO) is a colorless, odorless, and poisonous gas produced by incomplete burning of carbon in fuels such as coal, oil, and wood. It is the most abundant primary pollutant, with more than three-quarters of U.S. emissions coming from highway vehicles and off-road equipment.

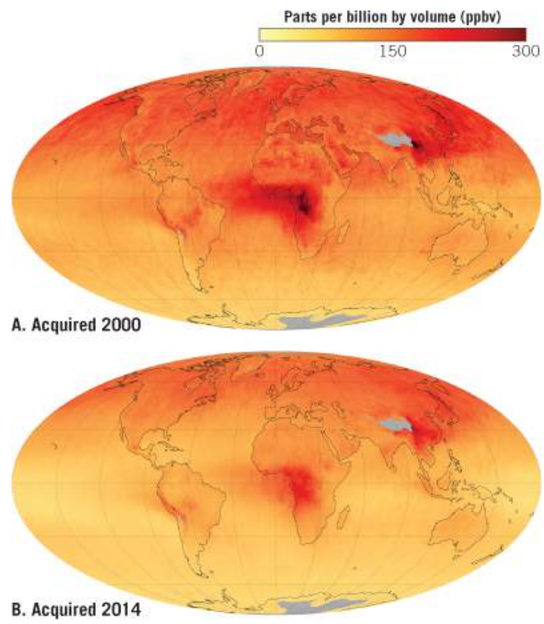
Although CO is quickly removed from the atmosphere, it can nevertheless be dangerous. Carbon monoxide enters the bloodstream through the lungs and reduces oxygen delivery to the body's organs and tissues. Because it cannot be seen, smelled, or tasted, CO can affect people without their realizing it. In small amounts, it causes drowsiness, slows reflexes, and impairs judgment. If concentrations are sufficiently high, CO inhalation can be fatal. Carbon monoxide poses a serious health hazard where concentrations can reach high levels, as in poorly ventilated tunnels and underground parking facilities. Many states require carbon monoxide detectors in homes.

In different parts of the world and in different seasons, the concentrations and sources change significantly. For example, in Africa, seasonal shifts in CO are tied to the widespread agricultural burning that shifts north and south of the equator. Fires used to clear forestlands are also an important source of CO in other regions, such as the Amazon Basin and parts of Southeast Asia. In the United States, Europe, and China, in contrast, the highest CO concentrations occur in and near urban areas with high concentrations of motor vehicles and factories.

The world maps in Figure 13.8 compare CO concentrations in 2000 and 2014. It is clear from these maps that CO concentrations have declined since 2000. This trend is largely attributable to the decline in pollutants being emitted by vehicles and industries.

Figure 13.8 **Carbon monoxide**

These maps show concentrations of carbon monoxide (CO) in the troposphere in **A.** 2000 and **B.** 2014. The data were collected by a sensor aboard NASA's *Terra* satellite. Yellow areas have little or no CO. Progressively higher concentrations are shown in orange and red. Although carbon monoxide output varies seasonally, the trend has shown a steady decline from 2000 to 2014.



Watch **Video: Global Carbon Monoxide Concentration**

Lead

Lead (Pb) is very dangerous because it accumulates in the blood, bones, and soft tissues. It can impair the functioning of many organs. Even at low doses, lead exposure is associated with damage to the nervous systems of young children.

In the past, automotive sources were the major contributor of lead emissions to the atmosphere because lead was added to gasoline to prevent engine knock. Since the EPA-mandated phaseout of leaded gasoline, lead concentrations in the air of U.S. cities have declined dramatically (see Table 13.1). Occasional violations of the lead air quality standard still occur near large industrial sources such as lead smelters.

Smog

Air pollution in urban and industrial areas is often called **smog**. The term, coined in 1905 by London physician Harold A. Des Veaux, was created by combining the words *smoke* and *fog*. Des Veaux's term was indeed an apt description of London's principal air pollution threat, which was associated with the products of coal burning coupled with periods of high humidity (see Severe & Hazardous Weather 13.1).

Severe & Hazardous Weather 13.1

The Great Smog of 1952

For centuries, the fogs of Britain's major cities were polluted with smoke. London was especially notorious for its poor air quality. In 1853, Charles Dickens described the smoke-laden fog in *Bleak House* and provided graphic accounts of London's foul air in several of his novels.

One of London's most infamous air pollution episodes occurred over a 5-day span in December 1952. During this time, caustic yellow smog shrouded the city, bringing premature death to thousands and inconvenience to millions (Figure 13.A). What conditions were responsible for this extraordinary event?

Figure 13.A Midday darkness

London's infamous Great Smog of 1952 persisted for 5 days and was responsible for thousands of deaths.

The weather was unusually cold, and Londoners were burning large quantities of coal to warm their homes. The smoke pouring from these chimneys as well as from the chimneys of London's many factories was not dispersed but rather accumulated in a shallow zone of very stable calm air. The "lid" for this trap was a substantial temperature inversion associated with a high-pressure center that had become established over the southern British Isles.

> In December 1952, caustic yellow smog shrouded London, bringing premature death to thousands.

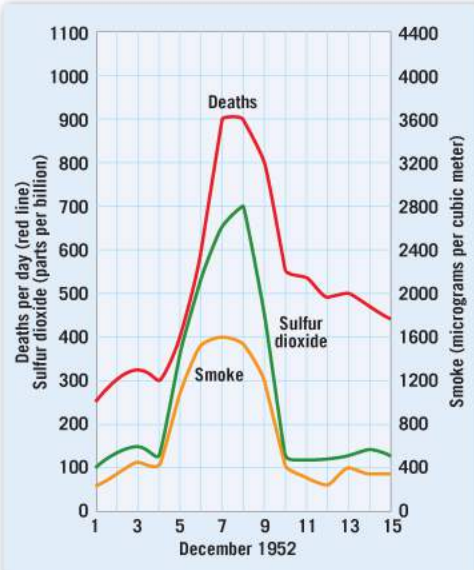
A fog layer 100–200 meters thick developed during the day on Friday, December 5. With nightfall came sufficient radiation cooling to produce an even denser fog. Of course, more and more smoke continued to collect in the saturated air. Visibility dropped to just a few meters in many areas. On Saturday, December 6, the weak winter Sun could not "burn away" the fog. The foul yellow mixture of smoke and fog became so thick that night that pedestrians could not find their way, even in familiar surroundings. People could not even see their own feet!

In central London, visibility remained below 500 meters continuously for 114 hours and below 50 meters for 48 hours. At Heathrow Airport, the visibility was less than 10 meters for 48 hours beginning on the morning of December 6. Winds did not sweep away the foul air until Tuesday, December 9.

This infamous episode of December 1952 came to be known as "The Great Smog." Experts agree that the Great Smog killed about 4000 people during that month (Figure 13.B). Furthermore, some researchers believe that an additional 8000 Londoners died in January and February 1953 due to the delayed effects of smog or lingering pollution. Other analyses disagree, blaming the latter deaths on influenza.

Figure 13.B Deaths and pollution during the Great Smog of 1952

Smoke and sulfur dioxide were monitored at various sites. The daily averages for 10 of these sites are shown here.



Even in a city where “pea soup” fogs were relatively common, this legendary event is generally viewed as the watershed event that gave rise to modern air pollution control in Great Britain as well as elsewhere in Western Europe and North America. Although London no longer experiences “great smogs,” foul air continues to plague big cities. The World Health Organization estimates that outdoor air pollution is responsible for about 800,000 deaths worldwide each year.

Weather Safety

While smog levels are nowhere near what they were in London in the 1950s, there are ways to protect yourself from smog.

- Check the Air Quality Index (AQI) forecast at www.airnow.gov.
- Avoid outdoor activities when the AQI value is high.

Apply What You Know

1. What was the source of the pollutants for the Great Smog?
2. Describe a meteorological factor that contributed to the build-up of pollutants.

Today, however, *smog* is used as a synonym for general air pollution and does not necessarily imply the smoke–fog combination. Therefore, when greater clarity is desired, we sometimes find the word "smog" preceded by such modifiers as "Los Angeles–type" or "photochemical."

Photochemical Smog

Photochemical smog consists of a noxious mixture of secondary pollutants, mainly gases and particles of nitrogen-based compounds and ozone, that produces a yellowish haze over cities (see Figure 13.5). Most photochemical smog forms when nitrogen oxides react with trace amounts of volatile organic compounds in the presence of sunlight—called a *photochemical reaction*. The result is the formation of a number of undesirable secondary pollutants that are very reactive, irritating, and toxic—and collectively produce photochemical smog. Some of the substances contained in photochemical smog are alkyl nitrite, peroxyacetyl nitrate, and nitric acid, which damage vegetation and irritate the eyes.

> Photochemical smog is produced by the chemical reaction of nitrogen oxides and VOCs in the presence of sunlight to produce a number of undesirable secondary pollutants.

Ozone and Photochemical Smog

In addition to various nitrogen-based irritants, a *major* component of photochemical smog is **ozone** (O_3). Recall from Chapter 1 that ozone is formed by natural processes in the stratosphere. However, when produced by photochemical processes near Earth's surface, ozone is considered a pollutant.

Like other components of photochemical smog, the reactions that create ozone are stimulated by strong sunlight; therefore, the formation of ozone is limited to daylight hours. Peaks occur in the afternoon following a series of hot, sunny, calm days. As you might expect, ozone levels are highest during the warmer summer months. Although May through October is typical, areas in the Sunbelt of the American Southwest may experience problems throughout the year.

According to the EPA, health effects attributed to ground-level ozone exposure include significant decreases in lung function and increased respiratory symptoms, such as chest pain and cough. Exposure to ozone can make people more susceptible to respiratory infection, result in lung inflammation, and aggravate preexisting respiratory diseases such as asthma. These effects generally occur while individuals, particularly children, are actively exercising, working, or playing outdoors. In addition, longer-term exposures to moderate levels of ozone may cause irreversible changes in lung structure, which could lead to premature aging of the lungs.

> A major component in most photochemical smog is ozone (O_3).

Ozone also affects vegetation, leading to reduced agricultural crop yields; reduced growth and survivability of tree seedlings; and increased plant susceptibility to disease, pests, and other environmental stresses such as harsh weather. In long-lived species, these effects may become evident only after many years or even decades of high ozone levels. Therefore ozone exposure has the potential for long-term effects on forest ecosystems.

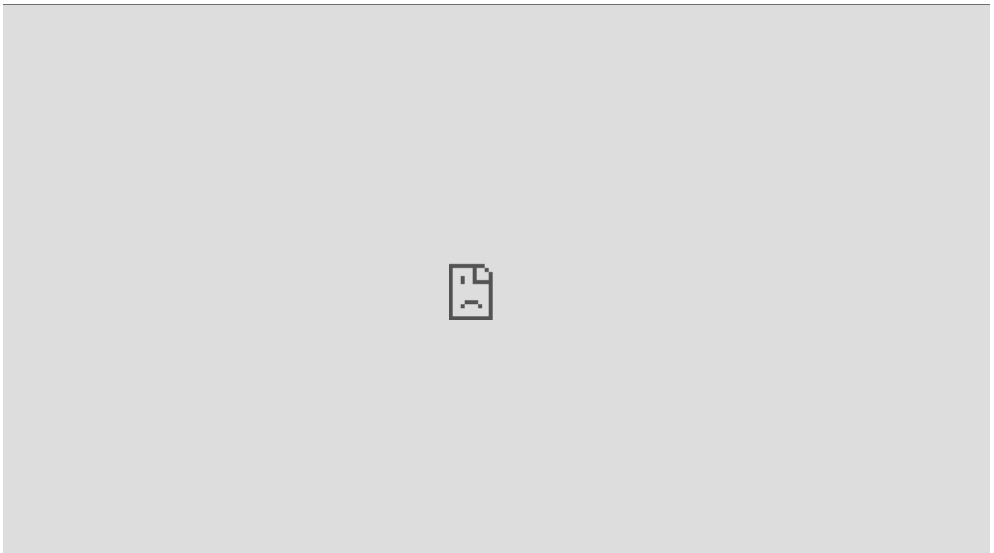
Volcanic Smog (Vog)

Although smog is largely a human-induced atmospheric hazard, nature is capable of creating it as well. A prime example occurs in active volcanic areas such as Hawaii. The satellite image in Figure 13.9 shows a haze hanging over the Pacific Ocean near the Big Island of Hawaii. This is a natural phenomenon called **vog**, short for *volcanic smog*. In this region, vog forms when sulfur dioxide from Kilauea volcano combines with oxygen and water vapor in the presence of strong sunlight.

Figure 13.9 Volcanic smog, called *vog*

The image from NASA's *Terra* satellite was acquired on December 9, 2009, and shows a dense vog-created haze over the Pacific near the Hawaiian Islands. Vog forms when sulfur dioxide (SO_2) from Kilauea volcano on the Big Island of Hawaii combines with oxygen and water vapor in the atmosphere to produce this natural form of smog.

Watch **Video: Smog Bloggers**



The tiny sulfate particles that make up vog are very reflective, which makes it easily observable when viewed from space. When the event pictured in Figure 13.9 occurred, SO_2 concentrations reached unhealthy levels in Hawaii Volcanoes National Park near the summit of Kilauea. In addition to reducing visibility, vog can aggravate respiratory problems. Vog is not confined to Hawaii—it occurs in other volcanic areas as well.

You might have wondered . . .

What are toxic air pollutants?

Toxic air pollutants are chemicals in the air that are known or suspected to cause cancer or other serious health effects, such as reproductive problems or birth defects. These substances are also commonly called *hazardous air pollutants* and *air toxins*. The EPA regulates 188 toxic air pollutants, including benzene, found in gasoline; perchloroethylene, used in some dry-cleaning facilities; and methylene chloride, used as a solvent and paint stripper.

Concept Checks 13.2

- Distinguish between a primary pollutant and a secondary pollutant.
- List the major primary pollutants. Which one is most abundant?
- What is a photochemical reaction? What is the major component of most photochemical smog?
- What is vog?

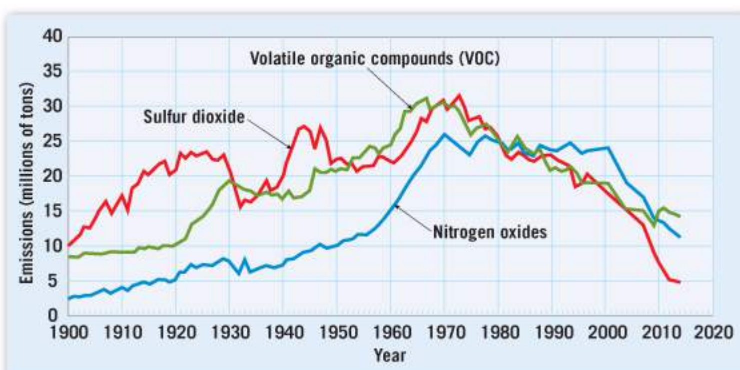
13.3 Trends in Air Quality

LO 3 Summarize trends in air quality since 1980.

Economic activity, population growth, and regulatory efforts to control emissions all influence the trends in air pollutant emissions. Until the 1970s, the greatest influences on emissions were related to the economy and population growth. Emissions *increased* as the economy and population grew, and they likewise *fell* in periods of economic recession. For example, dramatic declines in emissions, particularly SO_2, in the 1930s, were due to the Great Depression (Figure 13.10).

Figure 13.10 Trends in national emissions 1900–2014

Prior to 1970, economic activity and population growth were major factors influencing the emissions of air pollutants. Emissions grew as the economy and population increased, and emissions declined during economic downturns. For example, dramatic declines in emissions in the 1930s were due to the Great Depression. Since 1970, much of the downward trend in emissions has been due to the Clean Air Act.



Emissions also increase as a result of shifts in the demand for various products. For instance, the tremendous upsurge in demand for gasoline following World War II increased emissions associated with petroleum refining.

It was not until the passage of the federal Clean Air Act in 1970 that major strides were made in reducing air pollution. This legislation created the Environmental Protection Agency and charged it with establishing air quality and emissions standards. Table 13.1 illustrates the considerable progress made in reducing air pollution after the 1980s.

Table 13.1 Air Quality and Emissions Trends (negative numbers indicate improvements in air quality)

	Percentage Change in Concentrations	
	1980–2015	**2000–2015**
NO_2	–60	–45
O_3 (8-hour)	–32	–17
SO_2	–84	–69
PM_{10} (24-hour)	—*	–36
$PM_{2.5}$ (annual)	—*	–37
CO	–84	–60
Pb	–99	–91
	Percentage Change in Emissions	
	1980–2014	**2000–2014**
NO_x	–55	–45
VOCs	–53	–16
SO_2	–81	–70
PM_{10}	–58	–16
$PM_{2.5}$	—*	–33
CO	–65	–51
Pb	–80	–50

*Data not available.

Establishing Standards

The Clean Air Act of 1970 mandated the setting of standards for four primary pollutants—particulates, sulfur dioxide, carbon monoxide, and nitrogen oxides—as well as the secondary pollutant ozone. At the time, these pollutants were recognized as being the most widespread and objectionable; lead was subsequently added to this list. Since the original Clean Air Act was implemented, it has been amended, and its regulations and standards have been revised periodically.

Today five primary pollutants and ozone are covered by the National Ambient Air Quality Standards. The standard for each pollutant shown in Table 13.2 is based on the highest level that can be tolerated by humans without noticeable ill effects, minus a 10–50 percent margin for safety.

Table 13.2 National Ambient Air Quality Standards

Pollutant	Standard Value	
Carbon monoxide (CO)		
8-hour average	9 ppm*	(10 mg/m^3)
1-hour average	35 ppm	(40 mg/m^3)**
Nitrogen dioxide (NO_2)		
Annual mean	0.053 ppm	(100 μg/m^3)***
Ozone (O_3)		
8-hour average	0.070 ppm	
Lead (Pb)		
Quarterly average		0.15 μg/m^3
Particulate < 10 micrometers (PM_{10})		
24-hour average		150 μg/m^3
Particulate < 2.5 micrometers ($PM_{2.5}$)		
Annual mean		15 μg/m^3
24-hour average		35 μg/m^3
Sulfur dioxide (SO_2)		
1-hour average	75 ppb†	

*ppm, parts per million.
**mg/m^3, milligrams per cubic meter of air. A milligram is one-thousandth of a gram.
***μg/m^3, micrograms per cubic meter. A microgram is one-millionth of a gram.
†ppb, parts per billion.
Source: U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards.

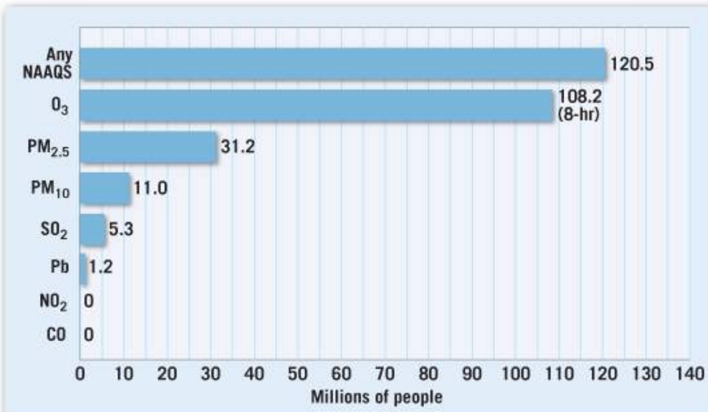
For some of the pollutants, both long-term and short-term levels are set. Short-term levels are designed to protect against acute effects, whereas the long-term standards were established to guard against chronic effects. *Acute* refers to pollutant levels that may be life-threatening within a period of hours or days. *Chronic* pollutant levels cause gradual deterioration of a variety of physiological functions over a span of years. It should be pointed out that standards are established using human health criteria and not according to their impact on other species or on atmospheric chemistry.

> The primary standard for the pollutants monitored by the EPA is based on the highest level that can be tolerated by humans without noticeable ill effects, minus a 10–50 percent margin for safety.

In 2015, more than 120 million people in the United States resided in counties that did not meet one or more air quality standards (Figure 13.11). It is clear from Figure 13.11 why the EPA describes ozone as our "most pervasive air pollution problem." The number of people living in counties that exceeded the ozone standard is greater than the total number of those living in counties affected by the other six categories of pollutants.

Figure 13.11 Number of people living in counties with air quality concentrations above the levels of the Air Quality Standards in 2015

Despite substantial progress in reducing emissions, there were still more than 120 million Americans living in counties with monitored air quality levels above the national standards.



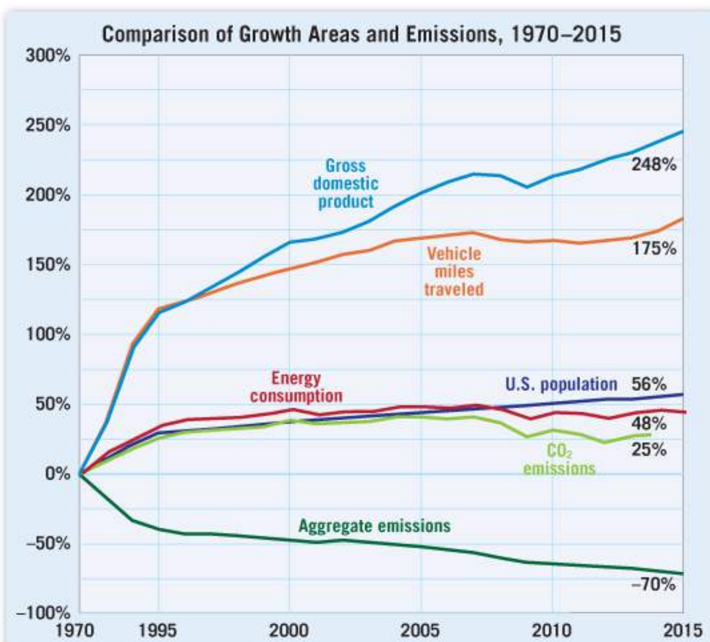
The fact that air quality standards have not yet been met in some places does not indicate a lack of progress. The United States has made significant strides in reducing air pollution. In 2015, emissions of the major primary pollutants shown in Figure 13.4 totaled about 91 million tons. By contrast, in 1970 when the Clean Air Act first became law, the same pollutants totaled about 301 million tons. The 2015 total is nearly 330 percent lower than the 1970 level. As Table 13.1 indicates, downward trends in all major pollutants in the United States between 1980 and 2014 have been substantial—an improvement achieved despite accelerated urban growth. However, pollutant control methods have not been as effective as expected in upgrading urban air quality.

> The downward trends in all major pollutants in the United States between 1990 and 2015 has been substantial.

An important reason for the slower-than-expected progress in improving air quality is related to growth. For example, between 1970 and 2015, *on a* *per-car basis*, emissions of primary pollutants were cut dramatically. However, during this same period, the U.S. population increased by about 56 percent, and vehicle miles traveled went up over 175 percent (Figure 13.12). In other words, pollution controls have improved air quality, but the positive effects have been partly offset by an increase in the number of vehicles on the road.

Figure 13.12 **Comparison of growth areas and emissions**

Between 1970 and 2015, gross domestic product increased almost 250 percent, vehicle miles traveled increased about 180 percent, energy consumption increased nearly 50 percent, and the U.S. population increased 56 percent. At the same time, total emissions of the six principal air pollutants decreased over 70 percent.



Air Quality Index

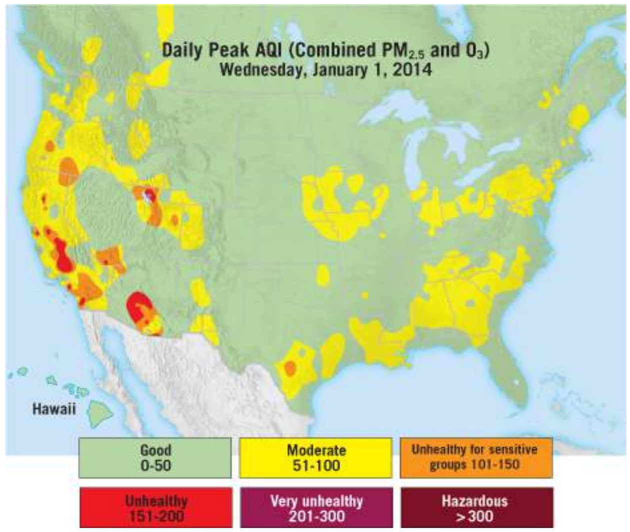
The **Air Quality Index (AQI)** is a standardized indicator for reporting daily air quality to the general public. Simply, it is an attempt to answer the question: How clean or polluted is the air today? It provides information on what health effects people might experience within a few hours or days of breathing polluted air. The EPA calculates the AQI for five major pollutants regulated by the Clean Air Act: ground-level ozone, particulate matter, carbon monoxide, sulfur dioxide, and nitrogen dioxide. Ground-level ozone and airborne particulates are the pollutants that pose the greatest risk to human health in the United States.

> The Air Quality Index (AQI) is a standardized indicator for reporting daily air quality to the general public.

The AQI scale runs from 0 to 500 (Figure 13.13). The higher the value, the greater the level of air pollution and the greater the health risk. An AQI value of 100 generally corresponds to the national air quality standard for the pollutant. Values below 100 are usually considered satisfactory. When values exceed 100, air quality is determined to be unhealthy—at first for sensitive groups and then, as values increase, for everyone else. Specific colors are assigned to each AQI category to make it easier for people to quickly understand whether air pollution is reaching unhealthy levels in their communities. To access the current AQI, visit www.airnow.gov.

Figure 13.13 Air Quality Index

The Air Quality Index (AQI) forecast map for January 1, 2014. To check the current map, go to www.airnow.gov.



> AQI values below 100 are usually considered satisfactory, whereas values exceeding 100 are considered unhealthy.

Concept Checks 13.3

- When was the Clean Air Act established? What are its criteria pollutants?
- Use Figure 13.10 to compare emissions of the primary pollutants for 1970 with emissions in 2014.
- What is the Air Quality Index?

13.4 Meteorological Factors Affecting Air Pollution

LO 4 Describe the influence of wind on air quality. Sketch a diagram showing a temperature inversion, and explain how it affects mixing depths.

The most obvious factor influencing air pollution is the quantity of contaminants emitted into the atmosphere. Still, experience shows that even when emissions remain relatively steady for extended periods, air quality often varies widely from one day to the next. Indeed, when air pollution episodes occur, they do not generally result from a drastic increase in the output of pollutants; instead, they occur because of changes in atmospheric conditions.

Perhaps you have heard the phrase "The solution to pollution is dilution." To a significant degree, this is true. If the air into which pollution is released is not dispersed, the air will become more toxic. Two of the most important atmospheric conditions affecting the dispersion of pollutants are the strength of the wind and the stability of the air. These factors are critical because they determine how rapidly pollutants are diluted when they mix with the surrounding air after leaving the source.

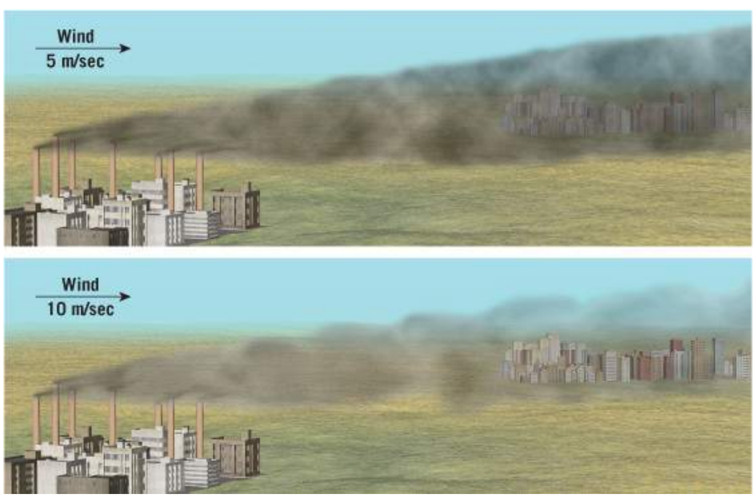
> The solution to pollution is dilution.

Wind as a Factor

The manner in which wind speed influences the concentration of pollutants is shown in Figure 13.14. Assume that a burst of pollution leaves a chimney stack every second. If the wind speed were 5 meters per second (12 miles per hour), the distance between each pollution "cloud" would be 5 meters. If wind speed increased to 10 meters per second, the "clouds" would be spaced twice as far apart, or 10 meters. Consequently, because of the direct effect of wind speed, the concentration of pollutants is twice as great for wind with a speed of 5 meters per second than it is for wind with a speed of 10 meters per second. It is easy to understand why air pollution problems seldom occur when winds are strong but rather are associated with periods when winds are weak or calm.

Figure 13.14 Effect of wind speed on the dilution of pollutants

Dilution of pollutants increases as wind speed increases.



A second aspect of wind speed influences air quality: The stronger the wind, the more turbulent the air. Thus, strong winds mix polluted air with a thicker layer of unpolluted air, thereby causing the pollution to become more dilute. Conversely, when winds are light, there is little turbulent mixing, and the concentration of pollutants remains high for a longer period of time (Figure 13.14).

> The stronger the wind, the more turbulent the air, which mixes polluted air with a thicker layer of unpolluted air.

The Role of Atmospheric Stability

Whereas wind speed governs the amount of air into which pollutants are mixed, atmospheric stability determines the extent to which *vertical* airflow will mix the pollution with cleaner air above. The vertical distance between Earth's surface and the height to which convection will carry pollution is called the **mixing depth**. The greater the mixing depth, the better the air quality.

Instability promotes vertical air movements and greater mixing depths. Because the Sun's heating of Earth's surface enhances convectional movements, mixing depths are usually greater during the afternoon hours. For the same reason, mixing depths during summer months are typically greater than during winter months.

By contrast, when air is stable, convectional motions are suppressed and mixing depths are small. When mixing depth is shallow, pollutants are confined to a much smaller volume of air, where concentrations can build, eventually reaching unhealthy levels.

Recall that **temperature inversions** produce stable atmospheric conditions, which restrict turbulence and, as a result, significantly affect mixing depths. Warm air overlying cooler air acts as a lid and prevents upward movement, leaving the pollutants trapped in a relatively narrow zone near the ground. This effect is dramatically illustrated by the photograph in Figure 13.15. Most of the air pollution episodes cited earlier were linked to the occurrence of temperature inversions that remained in place for many hours or days.

Figure 13.15 Air pollution in downtown Los Angeles

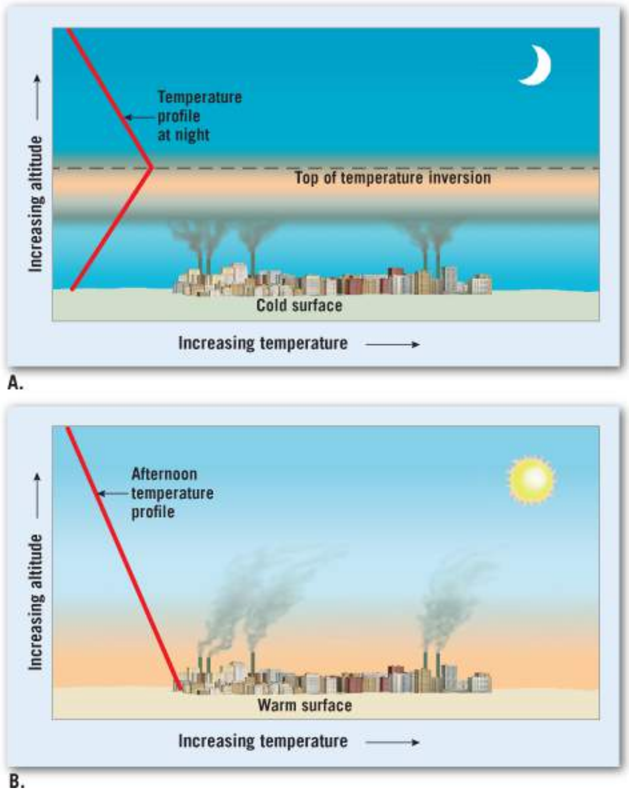
Temperature inversions act as lids that trap pollutants below.

Surface Temperature Inversions

Solar heating tends to produce high surface temperatures during the afternoon, which, in turn, increase the environmental lapse rate and render the lower air unstable (see Chapter 4). During nighttime hours, however, the opposite situation may occur: Temperature inversions, which result in very stable atmospheric conditions, can develop close to the ground. These surface inversions form because the ground is a more effective radiator than the air above. Therefore, radiation from the ground on a clear night causes more rapid cooling at the surface than higher in the atmosphere. Consequently, the coldest air is found next to the ground, yielding a vertical temperature profile resembling the one shown in Figure 13.16A. Once the Sun rises, the ground is heated, and the inversion disappears (Figure 13.16B).

Figure 13.16 Surface temperature inversion

A. A generalized temperature profile of a surface inversion. **B.** The temperature profile changes after the Sun has heated the surface.



Although usually rather shallow, surface inversions may be deep in regions where the land surface is uneven. Because cold air is denser than warm air, the chilled air near the surface gradually drains from the uplands and slopes into adjacent lowlands and valleys. As might be expected, this deeper surface inversion will not dissipate as quickly after sunrise. Thus, although river valleys are often preferred sites for manufacturing because they afford easy access to water transportation, they are also more likely to experience relatively thick surface inversions that in turn will have a negative effect on air quality.

Inversions Aloft

Many extensive and long-lived air pollution episodes are linked to temperature inversions that develop in association with the sinking air that characterizes centers of high air pressure (see Severe & Hazardous Weather 3.2). As the air sinks to lower altitudes, it is compressed, and so its temperature rises. Because turbulence is almost always present near the ground, this lowermost portion of the atmosphere is generally prevented from participating in the general subsidence. Thus, an inversion develops aloft between the lower turbulent zone and the subsiding warmer layers above. Such inversions are called **subsidence inversions** (Figure 13.17).

Severe & Hazardous Weather 13.2

Viewing an Air Pollution Episode from Space

In early October 2010, a high-pressure system settled over eastern China, deteriorating air quality. By October 9, China's National Environmental Monitoring Center declared air quality to be *poor* to *hazardous* around Beijing and in 11 eastern provinces. Citizens were advised to take measures to protect themselves. Visibility was reduced to 100 meters (330 feet) in some areas, and news outlets reported that at least 32 people died in traffic accidents caused by the poor visibility. Thousands suffered with asthma and other respiratory difficulties.

Instruments on NASA's *Aqua* and *Terra* satellites captured the natural-color view of this air pollution episode, shown in Figure 13.C. The milky white and gray covering the right portion of the image is smog, while the brighter white patches are clouds. Another image from NASA's *Aura* satellite shows levels of aerosols (Figure 13.D). The Aerosol Index indicates the presence of ultraviolet light–absorbing particles—largely smoke from agricultural burning and industrial processes. Figure 13.D shows that some areas had an aerosol index of 3.5. At an index value of 4, aerosols are so dense that you would have difficulty seeing the midday sun.

Figure 13.C **Serious air pollution plagues a portion of China**

This satellite image from October 8, 2010, captures the extent of the pollution episode.

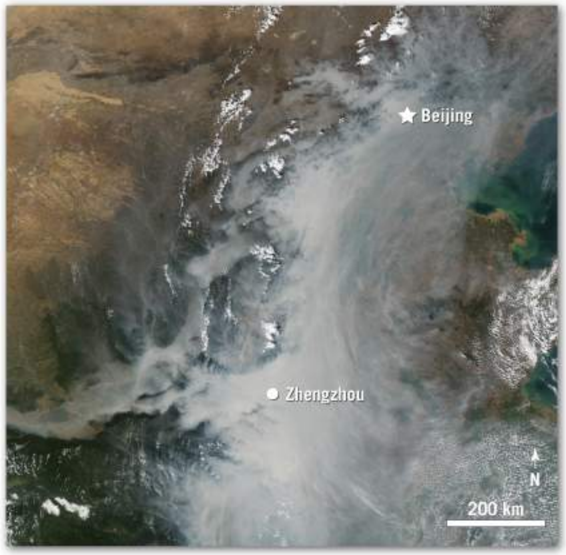
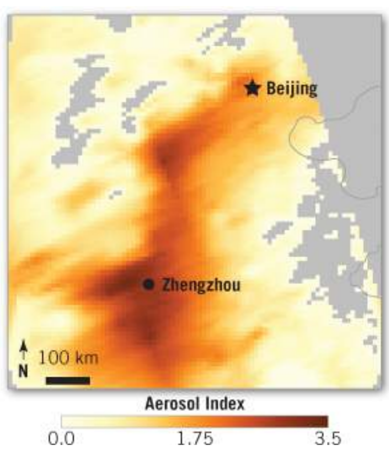


Figure 13.D **Aerosols**

This satellite image shows the extremely high levels of aerosols associated with the October 2010 air pollution episode in China.



> Thousands suffered with asthma and other respiratory difficulties.

High levels of sulfur dioxide were also recorded during this pollution event. The primary source of sulfur dioxide is coal-burning power plants and smelters. Peak concentrations were 6 to 8 times normal levels for China and 20 times normal levels for the United States.

On October 11, the weather changed—stagnant air associated with high pressure was replaced when a cold front brought cleansing rain and strong winds that cleared the sky.

Weather Safety

To protect yourself on days with high particulate concentrations in the air:

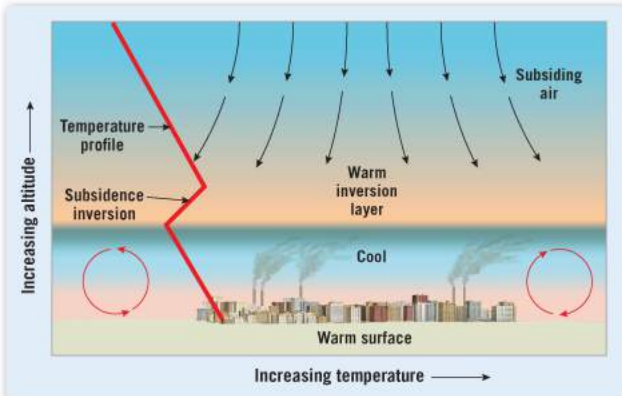
- Wear a surgical mask if you must be outdoors.
- Wear reading glasses, not contact lenses.
- Use caution when driving.

Apply What You Know

1. In the episode described here, what was the source of the sulfur dioxide pollution?
2. What was the source of most of the aerosols?

Figure 13.17 Subsidence inversion

Inversions aloft frequently develop in association with slow-moving centers of high pressure, where the air aloft subsides and warms by compression. The turbulent surface zone does not subside as much. Thus, an inversion often forms between the lower turbulent zone and the subsiding layers above.



The air pollution that plagues Los Angeles is frequently related to inversions associated with the subsiding eastern portion of the subtropical high over the North Pacific. In addition, the adjacent cool waters of the Pacific Ocean and the mountains surrounding the city compound the problem. When winds move cool air from the Pacific into Los Angeles, the warmer air that is pushed aloft creates or strengthens an inversion aloft that acts as an effective lid. Because the surrounding mountains keep the smog from moving farther inland, air pollution is trapped in the basin until a change in weather brings relief. Clearly, the geographic setting of a place can significantly contribute to air quality problems. The Los Angeles area is an excellent example.

> Inversions prevent rising motion and as a result traps air pollution.

You might have wondered . . .

I've heard that wood-burning fireplaces and stoves can be significant sources of air pollution. Is that actually the case?

Yes. Wood smoke can build up in areas where it is generated and expose people to high levels of air pollution, especially on cold nights when there is a temperature inversion. Wood smoke contains significant quantities of particulates and much higher levels of hazardous air pollutants, including some cancer-causing chemicals, than smoke from oil- and gas-fired furnaces. Some communities now ban the installation of conventional fireplaces or woodstoves that are not EPA certified.

Concept Checks 13.4

- Are most air pollution episodes triggered by a dramatic increase in the output of pollutants? Explain.
- Describe two ways in which wind influences air quality.
- What is *mixing depth*? How does it relate to air quality?
- Contrast the formation of a surface temperature inversion with an inversion aloft.

13.5 Acid Precipitation

LO 5 Discuss the formation of acid precipitation and list some of its effects on the environment.

Burning large quantities of fossil fuels, primarily coal and petroleum products, releases millions of tons of sulfur dioxide and nitrogen oxides into the atmosphere each year in the United States. In 2015, the total was 17.2 million tons. Through a series of chemical reactions, some of these primary pollutants are converted into acids that then fall to Earth's surface as rain or snow. This process, termed *wet deposition*, is what we think of as *acid rain*. By contrast, solid acidic particles that fall to the ground in the absence of water are called *dry deposition*. Dry-deposited particles can be washed from the surface by rain, making the runoff quite acidic. About half of the acidity in the atmosphere falls back to the surface as dry deposition.

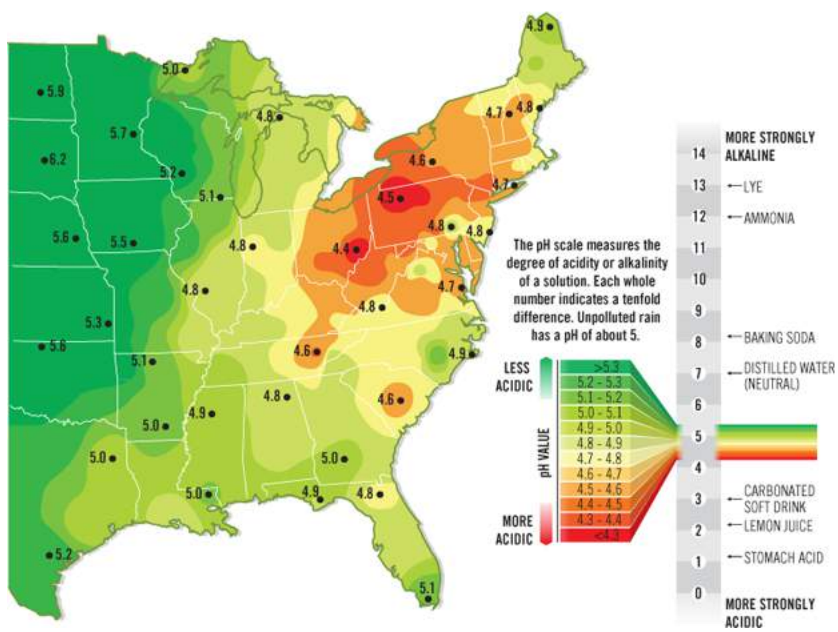
Extent and Potency of Acid Precipitation

Rain is naturally slightly acidic. When carbon dioxide from the atmosphere is dissolved by a raindrop, it becomes weak carbonic acid. Small amounts of other naturally occurring acids also contribute to the acidity of precipitation.

Studies in uncontaminated remote areas have shown that clean precipitation usually has a pH between 5 and 5.5 (Figure 13.18). However, in areas within several hundred kilometers of large centers of human activity, precipitation tends to have much lower pH values—meaning it is more acidic. Typical **acid precipitation** has a pH value of about 4—about 10 times more acidic than clean rainfall.

Figure 13.18 Precipitation pH values for the United States in 2011

In the United States, acid precipitation is most severe in the Northeast.



Acid rain has been widespread in Northern Europe and eastern North America for some time (Figure 13.18). Studies have also shown that acid rain occurs in many other regions, including Japan, China, Russia, and parts of South America. In addition to local pollution sources, a portion of the acidity found in the northeastern United States and eastern Canada originates hundreds of kilometers away, in industrialized regions to the south and southwest. This situation occurs because many pollutants remain in the atmosphere for periods as long as 5 days, during which time the prevailing winds may transport them great distances.

A primary reason for widely dispersed pollution is our desire to reduce pollution in the immediate vicinity of a source. Taller smoke stacks improve local air quality by releasing pollutants into the stronger and more persistent winds that exist at greater heights. Although such stacks enhance dilution and dispersion, they also promote the long-distance transport of these unwanted emissions. Hence, individual plumes with pollution concentrations considered too dilute to be a direct health or environmental threat locally will eventually contribute to pollution problems at distant locations.

Effects of Acid Precipitation

Acid rain looks, feels, and tastes just like clean rain. Swimming in an acid lake is no more dangerous than swimming in water that has not been affected by acid rain. Nevertheless, the sulfur dioxide and nitrogen oxide pollutants that cause acid rain damage human health. These gases interact in the atmosphere to form tiny droplets of sulfuric and nitric acid that can be transported long distances by winds and inhaled into lungs. These particles have been shown to aggravate heart problems and lung disorders such as asthma and bronchitis.

The damaging effects of acid rain on the environment are believed to be considerable in some areas and imminent in others. The best-known effect of acid precipitation is the lowering of pH in thousands of lakes and streams in Scandinavia and eastern North America. This has been accompanied by substantial increases in dissolved aluminum leached from the soil by the acidic water that, in turn, is toxic to fish. Consequently, some lakes are virtually devoid of fish, whereas others are approaching this condition. Furthermore, ecosystems are characterized by many interactions at many levels of organization, which means that evaluating the effects of acid precipitation on these complex systems is difficult and expensive—and far from complete.

Even within small areas, the effects of acid precipitation can vary significantly from one lake to another. Much of this variation is related to the nature of the soil and rock materials in the area surrounding the lake. Because minerals such as calcite in some rocks and soils can neutralize acid solutions, lakes surrounded by such materials are less likely to become acidic. In contrast, lakes that lack this buffering material can be severely affected. Even so, over a period of time, the pH of lakes that have not yet been acidified may drop as the buffering material in the surrounding soil becomes depleted.

Acid precipitation may also reduce agricultural crop yields and impair the productivity of forests. Acid rain not only harms the foliage but also damages roots and leaches nutrient minerals from the soil (Figure 13.19). Finally, acid precipitation promotes the corrosion of metals and contributes to the destruction of stone structures (Figure 13.20).

Figure 13.19 **Damage to forests by acid precipitation**

These trees in the Appalachian Mountains of North Carolina are examples of damage caused by acid precipitation.

Figure 13.20 Acid rain accelerates chemical weathering

Although we expect rock to gradually decompose, many stone monuments have succumbed prematurely because of accelerated chemical weathering linked to acid precipitation.

Watch Video: Hello Crud

The emission reductions in nitrogen oxides and sulfur dioxide noted earlier in the chapter have not only contributed to improved air quality but have also led to reductions in the acidity of precipitation in many areas (see Figure 13.10). Long-term monitoring of lakes and streams has shown that some acid-sensitive waters have experienced the beginnings of recovery. Nevertheless, although progress has been made, acid precipitation remains a complex and global environmental problem.

Eye on the Atmosphere 13.2

This tall smokestack is part of a coal-fired electricity-generating plant located in a valley in the rolling hills of West Virginia. Tall stacks are commonly associated with such power plants as well as with many factories. An extensive radiation fog is hugging the ground.

Apply What You Know

1. Is the time of day shown here more likely early morning or mid-afternoon? Explain.
2. Sketch a simple graph illustrating the likely vertical temperature profile at the time the photo was taken.
3. List two reasons why the air quality impact on the local area is reduced.

Concept Checks 13.5

■ Which primary pollutants are associated with the formation of acid precipitation?

■ Based on the map in Figure 13.18, where in the United States is precipitation most acidic?

■ What are some environmental effects of acid precipitation?

Concepts in Review

13.1 The Air Pollution Threat

LO 1 Name several natural sources of air pollution and identify those that are enhanced by human activity.

- Air pollution shortens human life spans and negatively impacts agriculture.
- Air is never perfectly clean. Volcanic ash, salt particles, pollen and spores, smoke, and windblown dust are all examples of natural air pollution.

13.2 Sources and Types of Air Pollution

LO 2 List the six major pollutants monitored by the Environmental Protection Agency (EPA) and discuss their effects on people and the environment.

Key Terms

air pollutant

aerosol

primary pollutant

secondary pollutant

particulate matter (PM)

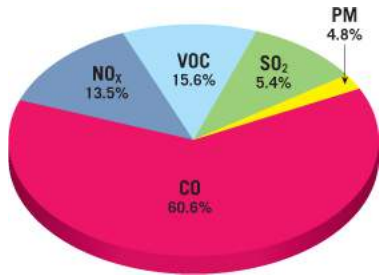
smog

photochemical smog

ozone

vog

- Air pollutants are airborne particles and gases that occur in concentrations that endanger the health and well-being of organisms or disrupt the orderly functioning of the environment.
- Pollutants can be grouped into two categories: primary pollutants and secondary pollutants.
- The major pollutants are particulate matter (PM), sulfur dioxide, nitrogen oxides, volatile organic compounds (VOCs), carbon monoxide, and lead. Atmospheric sulfuric acid and ground-level ozone are examples of secondary pollutants.
- Air pollution in urban and industrial areas is often called smog. Photochemical smog, a noxious mixture of gases and particles, is produced when strong sunlight triggers photochemical reactions in the atmosphere. A major component of photochemical smog is ozone.



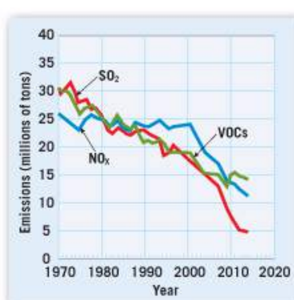
13.3 Trends in Air Quality

LO 3 Summarize trends in air quality since 1980.

Key Term

Air Quality Index (AQI)

- Although considerable progress has been made in controlling air pollution, the quality of the air we breathe remains a serious public health problem.
- Economic activity, population growth, meteorological conditions, and regulatory efforts to control emissions all influence the trends in air pollution.
- The Clean Air Act of 1970 mandated standards for four of the primary pollutants—particulate matter, sulfur dioxide, carbon monoxide, and nitrogen oxides—as well as the secondary pollutant ozone. In 2015, emissions of the major primary pollutants in the United States were about 70 percent lower than in 1970.



13.4 Meteorological Factors Affecting Air Pollution

LO 4 Describe the influence of wind on air quality. Sketch a diagram showing a temperature inversion, and explain how it affects mixing depths.

Key Terms

mixing depth

temperature inversion

subsidence inversion

- When air pollution episodes take place, they do not generally result from a drastic increase in the output of pollutants; instead, they occur because of changes in atmospheric conditions.
- Two of the most important atmospheric conditions affecting the dispersion of pollutants are (1) the strength of the wind and (2) the stability of the air.
- Strong winds improve air quality by diluting and dispersing pollutants.
- Atmospheric stability determines the extent to which vertical motions will mix the pollution with cleaner air above the surface layer. A temperature inversion represents a situation in which the atmosphere is very stable and the mixing depth is significantly restricted.
- When an inversion exists and winds are light, high pollution concentrations are to be expected in areas where pollution sources exist.

13.5 Acid Precipitation

LO 5 Discuss the formation of acid precipitation and list some of its effects on the environment.

Key Term

acid precipitation

- In most areas within several hundred kilometers of large urban centers, rainwater is more acidic (pH values are 5 or less) than rainwater in unpopulated areas.
- Acid precipitation (acidic rain or snow) forms when sulfur and nitrogen oxides produced as by-products of combustion and industrial activity are converted into acids by chemical reactions in the atmosphere.
- Wind carries combustion compounds from sources to the sites where they are deposited, and these components are transformed into acidic substances while in the air.
- The damaging effects of acid precipitation on the environment include the lowering of pH in thousands of lakes globally. Besides producing water that is toxic to fish, acid precipitation has also detrimentally altered many complex ecosystems.

Exercises and Online Activities

Mastering Meteorology™

For instructor-assigned homework, test prep resources, and other learning materials, visit **Mastering Meteorology.**

Review Questions

1. Is wood smoke a natural or human-made source of pollution?
2. Provide three examples of human sources of primary pollutants.
3. What is a secondary pollutant?
4. List and describe the health effects of the six primary pollutants.
5. What role do photochemical reactions play in creating pollution?
6. How does vog differ from smog?
7. Which pollutants are regulated by the Clean Air Act of 1970? How have emissions for these pollutants changed since 1970?
8. Significant strides have been made in reducing air pollution even though the standards have not been met in some areas. Explain this statement.
9. Why has progress in reducing air pollution been slower than expected?
10. Explain why pollution levels over a city might vary from one week to the next.
11. Describe how atmospheric stability influences pollution concentrations.
12. Explain why surface temperature inversions often form overnight.
13. Describe how most inversions aloft are generated.
14. What is the pH scale? What is the pH of clean rain?
15. Describe the effects of acid precipitation on humans and on the environment.

Give It Some Thought

1. **1.** In Chapter 1 you learned that we should be concerned about ozone depletion in the atmosphere. But based on the information presented in this chapter, it seems like getting rid of ozone would be a good idea. Can you clarify this apparent contradiction?
2. **2.** Table 13.1 shows trends in air quality and emissions. Explain why ozone (O_3) appears on the “Percentage change in concentrations” portion of the table but does not appear on the “Percentage change in emissions” portion.
3. **3.** The average motor vehicle today emits *much less* pollution than did the vehicles of 30 or 40 years ago. Why have the positive effects of this sharp reduction *not* been as great as we might have expected? In your explanation, include information from one of the graphs in this chapter.
4. **4.** Motor vehicles are a major source of air pollutants. Using electric cars, such as the one pictured here, is one way to reduce emissions from this source. Although these vehicles emit little or no pollution directly into the air, can they still be connected to the emission of primary pollutants? If so, explain.

5. **5.** Assume that you are at an airport in a large urban area. The city is experiencing an air quality alert, and haze reduces visibility. As your plane climbs after take-off, the air suddenly becomes much cleaner. Provide a likely explanation for the sudden change.

6. A glance at a cross section of a warm or cold front (see Figures 9.2 and 9.3) shows warm air *above* cool or cold air; that is, it shows a temperature inversion. Although temperature inversions are associated with fronts, they have little adverse effect on air quality. Why is this the case?
7. Ozone is sometimes called a “summer pollutant.” Why is summer also “ozone season”?
8. The use of tall smokestacks improves local air quality. However, tall stacks may contribute to pollution problems elsewhere. Explain.

Beyond the Textbook

Air Quality*

The quality of the air is determined by the concentration of particulates and chemical compounds. Air quality is measured around the world, and alerts are issued when the air becomes unhealthy.

Activities

Go to the Real-time Air Quality Index Visual Map at http://aqicn.org/map/ to see current Air Quality Index (AQI) measurements. Zoom out to see the entire world map.

1. List three countries that have the high AQI values (over 200). What are some of the highest values shown on the map?
2. List some regions that have the lowest AQI values.

Click on a country (from the bar above the map) that has stations with very high AQI. Click on a station with high AQI, and then click the link to see the full report.

3. What is the name of this location, and when was this station data updated?
4. What is the AQI value, and what is the danger level?
5. Which types of air pollution are monitored at this station? What type of pollution is responsible for the high AQI value?
6. What are the sources for these pollutants, and what are the adverse effects they cause?
7. Do any of the pollutants exhibit a diurnal cycle? If so, which one(s)?
8. What is air quality forecast for the next few days?
9. Based on the forecast, is there a relationship between temperature and air quality? What is this relationship?

Go back to the map and zoom into a station close to your own location.

10. Repeat steps 3 through 9, and summarize the differences between the two stations you examined.

* This activity was modified from Geosystems by Robert W. Christopherson.

Chapter 14 The Changing Climate

Glaciers are sensitive to changes in temperature and precipitation and therefore provide clues about changes in climate. Like most other glaciers in Alaska, Margerie Glacier in Glacier Bay National Park is steadily retreating into the mountains.

Focus on Concepts

Each statement represents the primary learning objective for the corresponding major heading within the chapter. After you complete the chapter, you should be able to:

1. Explain how unraveling past climate change is related to the climate system (14.1).
2. Describe several ways to detect evidence of climate change (14.2).
3. Discuss four natural phenomena that cause climate change (14.3).
4. Summarize the nature and cause of the atmosphere's changing composition since about 1750. Describe the climate's response (14.4).
5. Contrast positive- and negative-feedback mechanisms and provide examples of each (14.5).
6. Suggest several likely consequences of global climate change (14.6).

Climate has a significant impact on humans and their activities, and likewise, humans have strongly impacted climate—the consequences of which are likely to continue for many centuries. The effects of climate change caused by humans could be very disruptive to future generations as well as to many other life-forms. This chapter examines evidence for climate change and the ways humans are modifying our planet's climate. The next chapter describes the world's major climate regions and explains how these are classified.

14.1 Climate Change

LO 1 Explain how unraveling past climate change is related to the climate system.

Research focused on human impacts on the environment has demonstrated that people are not only responsible for some forms of air pollution, described in the previous chapter, but are inadvertently changing Earth's climate as well. Unlike changes in the geologic past, which were natural climate variations, modern climate change is dominated by human influences, and these changes significantly exceed the bounds of natural variability.

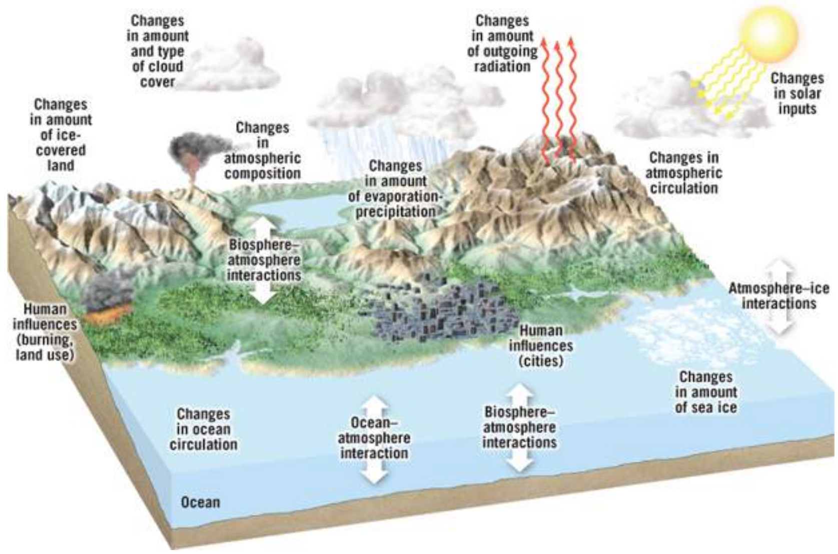
The Climate System

Throughout this text, you have seen that Earth is a complex system consisting of many interacting parts. A change in any one part can produce changes in any or all of the other parts—often in ways that are neither obvious nor immediately apparent. Key to understanding climate change and its causes is the fact that climate is related to all parts of the Earth system.

Earth's **climate system** derives its energy from the Sun and includes the atmosphere, hydrosphere, lithosphere (solid Earth), biosphere, and cryosphere. The first four spheres were discussed in Chapter 1; the **cryosphere** refers to the portion of Earth's surface where water is in solid form. This includes snow, glaciers, sea ice, freshwater ice, and frozen ground (termed *permafrost*). The climate system, illustrated in Figure 14.1, involves the exchanges of energy and moisture among the five spheres. These exchanges link the atmosphere to the other spheres, resulting in a complex interactive unit. When one part of the climate system changes, the other components react.

Figure 14.1 Earth's climate system

Many interactions occur among the various components on a wide range of space and time scales, making the system extremely complex.



> The *climate system* involves the exchanges of energy and moisture among the five spheres.

Every day scientists make new discoveries that improve our understanding of climate system interactions. One example came from a study of glacial melting on Mount Kilimanjaro. The obvious villain was global warming, but scientists discovered that the real culprit was deforestation on Mount Kilimanjaro. Mass removal of trees decreased the humidity in the air, which in turn decreased the snowfall. Many other glaciers have been studied, and much of their decline has been directly linked to a warming planet—but this example shows that land-use changes, such as deforestation, can also have far-reaching effects. There are likely many other undiscovered mechanisms—both natural and caused by humans—that can affect climate.

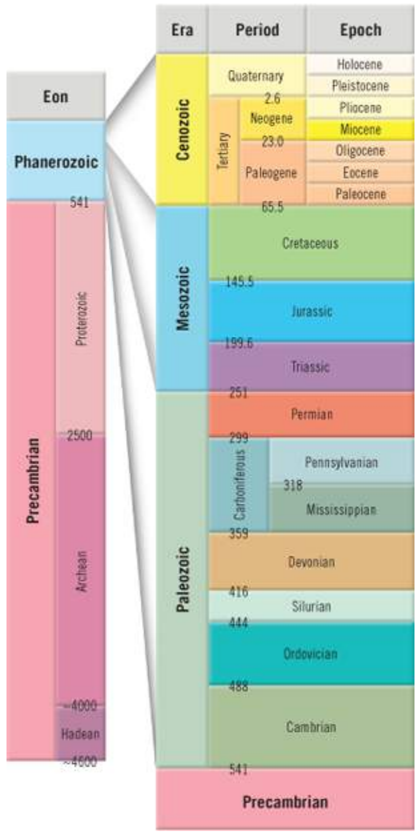
How Has Climate Changed in the Distant Past?

Using fossils and many other geologic clues, scientists have reconstructed Earth's climate going back hundreds of millions of years. Over long time scales, Earth's climate can be broadly characterized as gradually alternating from being a warm "greenhouse" or a cold "icehouse." The warm greenhouse climates are also referred to as *interglacial* periods and the cold icehouse climates as *glacial* periods. During greenhouse times, there is little, if any, permanent ice at either pole, and the middle and high latitudes experience warmer-than-average temperatures. By contrast, during icehouse conditions, the global climate is cold enough to support extensive ice sheets at both poles and colder-than-average temperatures in the middle and high latitudes.

Earth's climate has gradually transitioned between these two categories a few times in the past 542 million years, a span known as the Phanerozoic ("visible life") eon (Figure 14.2). The rocks and deposits of the Phanerozoic eon contain abundant fossils that document major environmental trends, the most recent of which occurred during the Cenozoic era.

Figure 14.2 **Geologic time scale**

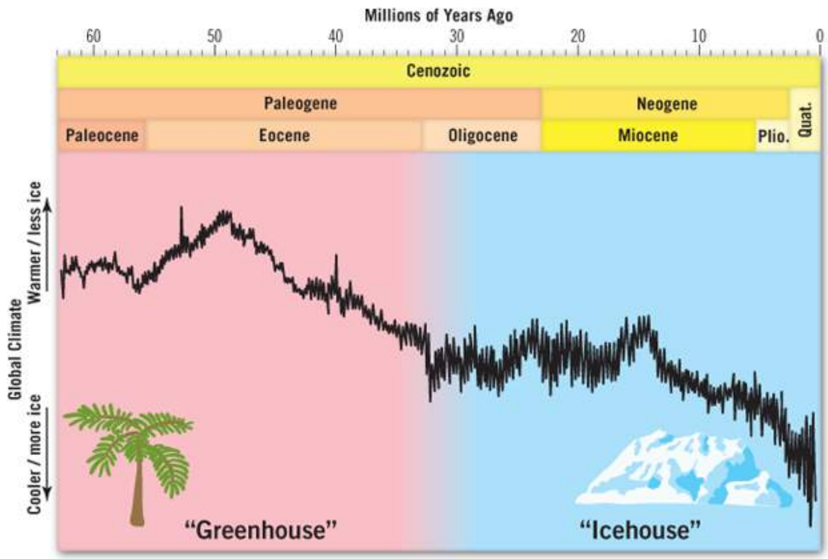
The time scale divides the vast 4.6-billion-year history of Earth into eons, eras, periods, and epochs. Numbers refer to millions of years before present.



The early Cenozoic was a time of greenhouse conditions like those the dinosaurs experienced during the preceding Mesozoic era. Peak temperatures occurred about 50 million years ago and were followed by a period of gradual cooling. By about 34 million years ago, permanent ice sheets were present at the South Pole, ushering in icehouse conditions (Figure 14.3). In North America, the lush "greenhouse" forests, marked by palm trees in Wyoming and banana plants in Oregon, were replaced by open grasslands. Grassland ecosystems are better suited for a cooler, drier "icehouse" climate. The grasslands of North America, in turn, supported large grazing mammals, including horses, deer, camels, rhinos, and elephants.

Figure 14.3 **Relative climate change during the Cenozoic era**

During the past 65 million years, Earth's climate shifted from being a warm "greenhouse" to being a cool "icehouse."



By about 2.6 million years ago (the start of the Quaternary period; see Figure 14.3), Earth's climate was cold enough to support large ice sheets at both poles. In the Northern Hemisphere, ice advanced nearly as far south as the present-day Ohio River and subsequently retreated to Greenland. For the past 800,000 years, this cycle of ice advance and retreat occurred about every 100,000 years. The last major ice sheet advance reached a maximum about 18,000 years ago. This period of glaciation is called the **Quaternary Ice Age**.

The next section examines how scientists decipher Earth's climate history. We then explore some natural causes of climate change before returning to the question of how humans have changed climate.

Concept Checks 14.1

- List the five parts of Earth's climate system.
- What is meant by a glacial period? An interglacial period?

14.2 Detecting Climate Change

LO 2 Describe several ways to detect evidence of climate change.

Climate varies not only from place to place, as examined in Chapter 15, but also over time. During the great expanse of Earth history, and long before humans were roaming the planet, there were many shifts—from warm to cold and from wet to dry and back again. Nearly every place on our planet has experienced wide swings in climate.

Proxy Data

The high-tech digital and precision instrumentation currently utilized to study the composition and dynamics of the atmosphere are recent inventions and therefore have been providing data for only a short time. To understand fully the behavior of the atmosphere and to anticipate future climate change, we must discover how Earth's climate has changed over broad expanses of time.

Instrumental records of climate go back only a few centuries, at best, and the further back we go, the less complete and more unreliable the data become. To overcome this lack of direct measurements, scientists reconstruct past climates by using *indirect* evidence called **proxy data**. The main goal of such work is to understand climates of the past, termed **paleoclimatology**, in order to assess potential future climate changes in the context of natural climate variability.

> Scientists decipher and reconstruct past climates mainly by using indirect evidence called *proxy data*.

Proxy data come from natural recorders of climate variability, such as glacial ice, seafloor sediments, fossil pollen, and tree-growth rings (Figure 14.4).

Figure 14.4 Ancient bristlecone pines

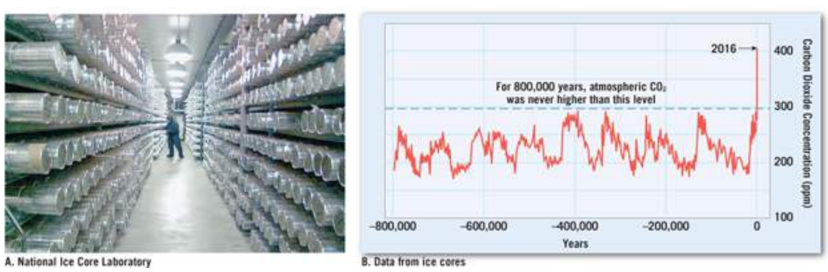
Some of these trees in California's White Mountains are more than 4000 years old. The study of tree-growth rings is one way that scientists reconstruct past climates.

Glacial Ice

Cores of glacial ice are an indispensable source of data for reconstructing past climates. Scientists collect ice cores mainly from the Greenland and Antarctic ice sheets using a drilling rig—a small version of an oil-well drill. A hollow shaft follows the drill head into the ice, and a cylindrical ice core is extracted (Figure 14.5A). Air bubbles trapped in ice cores contain samples of the atmosphere at the time snow was converted to ice. From these trapped air samples, researchers measure the concentration of greenhouse gases such as carbon dioxide and methane. Whereas modern continuous measurements of the atmosphere, taken at Mauna Loa observatory in Hawaii, extend back only to 1958, ice core data allows us to "see" thousands of years into the past.

Smartfigure 14.5 Ice cores: Important sources of climate data

A. The National Ice Core Laboratory is a physical plant for storing and studying cores of ice taken from glaciers around the world. These cores represent a long-term record of the composition of the atmosphere in the distant past. **B.** This graph, showing carbon dioxide variations over the past 800,000 years, is derived from oxygen-isotope analysis of ice cores recovered from the Antarctica and Greenland Ice Sheets.



Watch **SmartFigure: The Climate Record in Glacial Ice**

> Air bubbles trapped in ice cores contain samples of the atmosphere at the time snow was converted to ice.

The longest ice core comes from East Antarctica at 75° south latitude, where the ice sheet is the thickest. A multinational team extracted a 10-centimeter (4-inch) ice core to a depth that exceeded 3 kilometers (2 miles). The analysis has provided climate and atmospheric data back 800,000 years—encompassing eight glacial-interglacial cycles (Figure 14.5B).

Antarctic ice cores show that the concentration of carbon dioxide (CO_2) during the past 800,000 years never exceeded 300 parts per million (ppm) until the early nineteenth century, when it started to rise (Figure 14.5B). In 2016, the concentration of CO_2 was over 400 ppm, which is about 40 percent higher than it was before the Industrial Revolution.

> Today the concentration of CO_2 is nearly 40 percent higher than it was before the Industrial Revolution.

Seafloor Sediments

Most seafloor sediments contain the tiny shells of microorganisms, including foraminifera, that once lived in the ocean. When these organisms die, their shells slowly settle to the floor of the ocean, where they become part of the sedimentary record (Figure 14.6). These seafloor sediments are important recorders of worldwide climate change because the numbers and types of organisms living near the sea surface change with the climate. Certain species are found in distinct environments, such as warm tropical waters, whereas others reside only in the subpolar oceans. By piecing together the specific type of organisms found in a given region during a particular time period, researchers can reconstruct past climate conditions.

Figure 14.6 Foraminifera

These single-celled amoeba-like organisms are extremely abundant and found throughout the world's oceans. These organisms are commonly used to study climate change during the Cenozoic era. The chemical composition of their hard parts depends on water temperature and the presence or absence of large ice sheets.

The sediment cores gathered by drilling ships and other research vessels have provided invaluable data that have significantly expanded our understanding of past climates. Because each year's sediments are stacked on top of older layers, sediment cores can be read as a timeline of natural events. One notable example of how seafloor sediments add to our understanding of climate change relates to the fluctuating climate conditions of the Quaternary Ice Age.

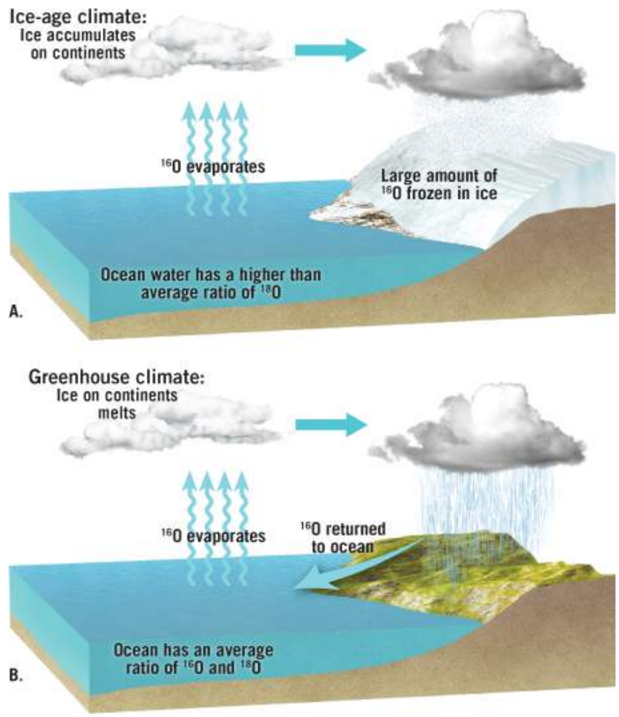
In addition, valuable information can be gathered by examining the fossilized calcium carbonate ($CaCO_3$) shells left behind by foraminifera. This is done by done by analyzing naturally occurring isotopes of oxygen found in the shells.

Oxygen-Isotope Analysis

The ratio of oxygen isotopes found in foraminifera shells tells us how much water was trapped in glacial ice, and hence the status of global climate, when these shells formed. **Oxygen-isotope analysis** is based on precise measurement of the *ratio* between two isotopes of oxygen: ^{16}O, which is the most common, and the heavier ^{18}O. A molecule of water (H_2O) can contain either ^{16}O or ^{18}O. However, water molecules containing the lighter ^{16}O isotope evaporate more readily than those with the heavier ^{18}O isotope (Figure 14.7A). Because of this difference, precipitation such as rain and snow is enriched in ^{16}O as compared to seawater. Thus, during periods of widespread glaciation, more of the lighter ^{16}O becomes trapped in glacial ice, so the concentration of ^{18}O in seawater is higher than average. The *higher* the $^{18}O/^{16}O$ ratio, the *cooler* the climate; and by contrast, the *lower* the ratio, the *warmer* the climate. Thus, oxygen-isotope data serve as proxy data for temperature (Figure 14.7B). A record of the changes of the $^{18}O/^{16}O$ ratio could tell scientists when ice ages occurred and, therefore, when the climate grew cooler.

Figure 14.7 The concentration of oxygen isotopes in seawater varies with climate

A. Water with lighter oxygen evaporates more readily and is locked up in the ice formed during an ice age. **B.** This water is returned to the oceans during warmer periods, changing the oxygen-isotope ratio.



> During periods of widespread glaciation, more of the lighter ^{16}O is trapped in glacial ice, so the concentration of ^{18}O in seawater is higher than average.

Fortunately, such a record can be found on the ocean floor. As foraminifera secrete their calcium carbonate ($CaCO_3$) shells, the prevailing $^{18}O/^{16}O$ ratio in seawater is reflected in the composition of their shells. When these organisms die, their hard parts settle to the ocean floor and become part of the sediment. Consequently, periods of extensive glacial activity can be determined from the oxygen-isotope ratio found in the shells of these and other microorganisms buried in deep-sea sediments. Oxygen-isotope analysis of foraminifera shells found in seafloor sediments also confirms the accuracy and reliability of climate data extracted from ice cores, discussed earlier.

Corals

Coral reefs are built by colonies of corals, invertebrates that live in warm, shallow waters, atop the hard material left behind by past corals. Because corals, like foraminifera, have hard skeletons built from the $CaCO_3$ extracted from the surrounding seawater, the ratio of ^{16}O to ^{18}O can be used to determine the temperature of the water at the time the coral reef was forming. Think of coral as another *paleothermometer* that reveals important data about climate variability in the world's oceans.

Oxygen-isotope analysis of coral can also serve as a proxy measurement for precipitation, particularly in areas where large variations in annual rainfall occur. High concentrations of ^{16}O (light oxygen) indicate that the area draining into the sea experienced heavy rains when the corals were forming. (Recall that rainwater contains a higher-than-average amount of light oxygen.)

Tree Rings

Tree rings, the concentric rings visible on a cross-section of a tree trunk, become larger in diameter outward from the center (Figure 14.8A). Every year in temperate regions, trees add a layer of new wood under the bark. Characteristics of each tree ring, such as size and density, reflect the environmental conditions (especially temperature and precipitation) that prevailed during the year when the ring formed. Favorable growth conditions produce a wide ring; unfavorable ones produce a narrow ring. Trees growing at the same time in the same region show similar tree-ring patterns.

Figure 14.8 Tree rings

A. These rings are useful records of past climate because the amount of growth (the thickness of a ring) depends on precipitation and temperature. **B.** Scientists are not limited to working with trees that have been cut down. Small, nondestructive core samples can be taken from living trees.

Watch Video: Climate, Crops, and Bees

Because a single growth ring is usually added each year, the age of the tree when it was cut can be determined by counting the rings. Further, if the year of cutting is known, the age of the tree and the year in which each ring formed can be determined by counting back from the outside ring. The dating and study of annual rings in trees is called **dendrochronology**. Fortunately, scientists are not limited to working with trees that have been cut down—small, nondestructive core samples can be taken from living trees (Figure 14.8B).

To make the most effective use of tree rings, dendrochronologists establish extended tree ring patterns known as *ring chronologies* by comparing the patterns of rings among trees of various ages in an area. (Even older chronologies have been produced by comparing ring patterns with those found in much older logs, cut years ago, that were found in old wooden structures.) If the same pattern can be identified in two samples, one of which has been dated, the second sample can be dated from the first by matching the common ring patterns. Tree-ring chronologies extending back for thousands of years have been established for some regions. Thus, tree rings can be used to reconstruct climate variations within a region for spans of thousands of years prior to human historical records.

Fossil Pollen

Climate is a major factor influencing the distribution of vegetation, so the nature of the plant community occupying an area at some past time serves as its climate proxy. Pollen and spores are parts of the life cycles of many plants and have very resistant cell walls, so these are often the most abundant, easily identifiable, and best-preserved plant fossils in sediments. Analyzing pollen from accurately dated sediments makes it possible to obtain high-resolution records of vegetation changes in an area. If the pollen recovered is indicative of an arid ecosystem, we can be fairly certain that when this vegetation was alive, the area was dry. Past climates can be reconstructed from such information.

Concept Checks 14.2

- What are proxy data? Explain why they are necessary in the study of climate change.
- Explain how past temperature and precipitation characteristics are determined by using oxygen-isotope analysis.
- Describe how each of the following are useful in the study of past climates: seafloor sediment, glacial ice, coral, tree rings, and fossil pollen.

14.3 Natural Causes of Climate Change

LO 3 Discuss four natural phenomena that cause climate change.

In this section we examine phenomena that trigger climate change but are unrelated to human activities. These phenomena include plate tectonics, variations in Earth's orbit, solar variability, and volcanic activity. Scientists believe that more than one of these mechanisms may interact to trigger a change. It is also worth noting that researchers have not identified a single mechanism that explains climate change on all time scales. A mechanism that explains variations over millions of years generally cannot explain fluctuations over hundreds of years.

Plate Tectonics and Climate Change

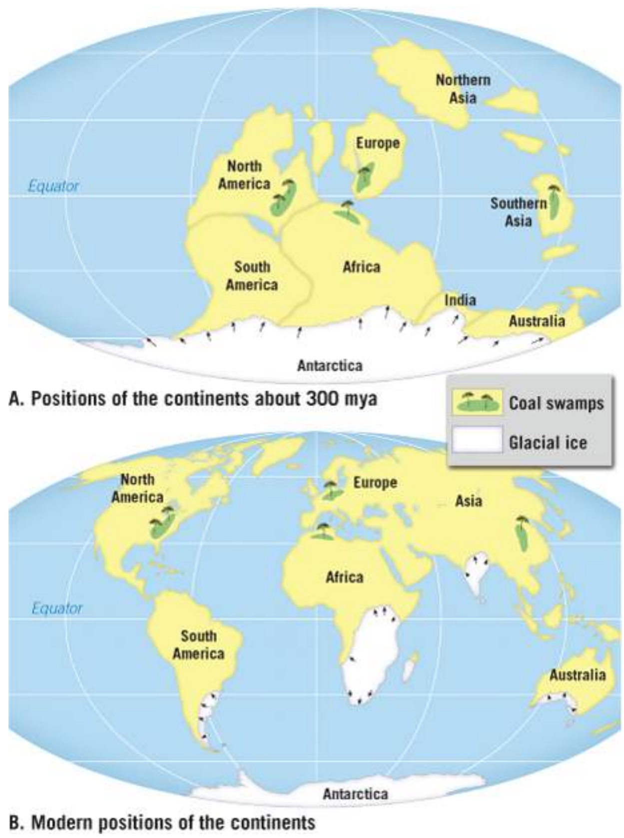
Over the past several decades, a revolutionary idea has emerged from the science of geology: **plate tectonics theory**. It states that the outer portion of Earth is made up of several vast rigid slabs, called *plates*, that move in relation to one another over a "weak" rock layer below. The plates move incredibly slowly; the average rate at which they move relative to each other is roughly the same rate at which human fingernails grow—a few centimeters a year.

As plates ponderously shift, continents also change position. This theory not only allows geologists to understand and explain many features of Earth's continents and oceans, but also provides climate scientists with a probable explanation for some hitherto unexplainable climate changes. For example, evidence of extensive glacial activity in portions of present-day Africa, Australia, South America, and India indicates that these regions experienced an ice age about 300 million years ago. During the same span of geologic time, large tropical swamps existed in several locations in the Northern Hemisphere. The lush vegetation in those swamps was eventually buried and converted to coal that comprise the major coalfields in the eastern United States and Northern Europe. This finding puzzled scientists for many years. How could the climate in Africa, Australia, South America, and India have been frigid, like Greenland and Antarctica, while the climates in North America and Europe were tropical?

Today scientists realize that the southern continents were joined together as part of the supercontinent termed *Pangaea*, located near South Pole (Figure 14.9A). This would account for the polar conditions required to generate extensive expanses of glacial ice over much of these landmasses. At the same time, this geography places today's northern continents nearer the equator and accounts for the tropical swamps that generated the vast coal deposits. Later, as the plates moved apart, portions of the landmass—each moving on a different plate—slowly migrated to their present locations. Thus, large fragments of glaciated terrain ended up in widely scattered subtropical locations (Figure 14.9B).

Figure 14.9 A late Paleozoic ice age explained by the theory of plate tectonics

Shifting tectonic plates sometimes move landmasses to latitudes where the formation of ice sheets is possible.



We now understand that during the geologic past, plate movements accounted for many other dramatic climate changes that occurred as landmasses shifted in relation to one another and moved to different latitudes. Changes in oceanic circulation must also have occurred, altering the transport of heat and moisture and, hence, the climate as well.

Because the rate of plate movement is so slow, appreciable changes in the positions of the continents occur only over *great* spans of geologic time. Thus, climate changes brought about by plate movements are extremely gradual and happen on a scale of millions of years. As a result, the theory of plate tectonics is not useful for explaining climate variations that occur on shorter time scales, such as tens, hundreds, or even thousands of years.

> Plate tectonics explains climate change on very long time scales—millions of years.

Variations in Earth's Orbit and Climate Change

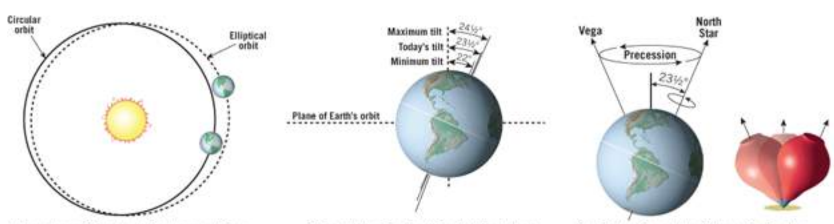
Geologic evidence indicates that the Quaternary Ice Age, which began about 2.6 million years ago, was characterized by numerous glacial advances and retreats associated with periods of global cooling and warming. Today scientists understand that the climate oscillations that characterized this ice age are linked to variations in Earth's orbit. This proposal, first developed by Serbian scientist Milutin Milankovitch, is based on the premise that variations in incoming solar radiation are a principal factor controlling Earth's climate.

Milankovitch formulated a comprehensive mathematical model based on the following elements:

1. Variations in the shape (**eccentricity**) of Earth's orbit about the Sun (Figure 14.10A)
2. Changes in **obliquity**—that is, changes in the angle that the axis makes with the plane of Earth's orbit (Figure 14.10B)
3. The wobbling of Earth's axis, called **precession** (Figure 14.10C)

Smartfigure 14.10 Orbital variations

Periodic variations in Earth's orbit are linked to alternating glacial and interglacial conditions during the Quaternary Ice Age.



A. The shape of Earth's orbit changes during a cycle that spans about 100,000 years. It gradually changes from nearly circular to more elliptical and then back again.

B. Today the axis of rotation is tilted about 23.5 degrees to the plane of Earth's orbit. During a cycle of 41,000 years, this angle varies from 22 to 24.5 degrees.

C. Earth's axis wobbles like a spinning top. Consequently, the axis points to different spots in the sky during a cycle of about 26,000 years.

Watch SmartFigure: Orbital Forcing of Ice Ages

Watch Animation: Orbital Variations and Climate Change

Using these factors, Milankovitch calculated variations in the receipt of solar energy and the corresponding surface temperature of Earth back in time, in an attempt to correlate these changes with the climate fluctuations of the Quaternary Ice Age. It should be noted that these factors cause little or no variation in the *total* solar energy reaching the ground. Instead, their impact is felt because they change the *degree of contrast between the seasons*. Somewhat milder winters in the middle to high latitudes mean greater snowfall totals, whereas cooler summers bring a reduction in snowmelt.

> The Milankovitch theory describes changes in Earth's eccentricity, obliquity, and precession, which in turn cause changes in climate.

Among the studies that added credibility to this hypothesis is one that examined deep-sea sediments. Through oxygen-isotope analysis of climatically sensitive microorganisms, the study established a chronology of temperature change going back nearly 500,000 years. This time scale of climate change was then compared to astronomical calculations of eccentricity, obliquity, and precession to determine whether a correlation existed. The authors concluded that changes in Earth's orbital geometry are the fundamental cause of the series of ice ages during the Quaternary period.

The study went on to predict a future trend toward a cooler climate and extensive glaciation in the Northern Hemisphere with two qualifications: (1) The prediction applied only to the *natural* component of climate change and ignored any human influence, and (2) it was a forecast of *long-term trends* because it must be linked to factors that have periods of 20,000 years and longer. Thus, even if the prediction is correct, it contributes little to our understanding of climate changes over briefer periods of tens to hundreds of years. This is because the cycles are too long to cause short-term variations in climate—like the current period of global warming.

> Orbital variations of Earth account for climate changes on time scales of tens to hundreds of thousands of years.

If orbital variations explain alternating glacial–interglacial periods, a question immediately arises: Why have glaciers been absent throughout most of Earth’s history? Prior to the plate tectonics theory, there was no widely accepted answer. Today we have a plausible answer: Because ice sheets form only on continents, landmasses must exist somewhere in the higher latitudes before an ice age can commence. Thus, it is likely that ice ages have occurred only when Earth’s shifting crustal plates have carried the continents from tropical latitudes to more poleward positions.

Solar Variability and Climate

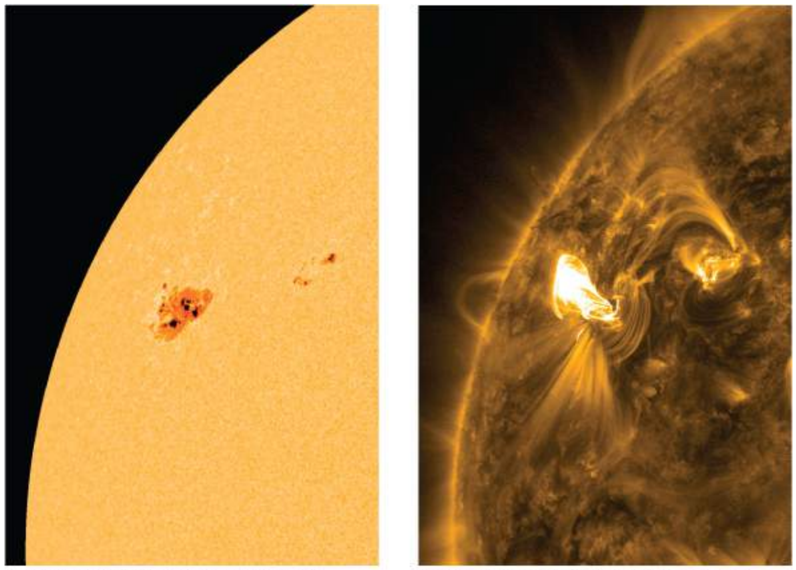
Among the most persistent hypotheses of climate change are those based on the Sun being a variable star with output of energy that varies through time. The effect of such changes would be direct and easily understood: Increases in solar output would cause the atmosphere to warm, and reductions would result in cooling. This notion is appealing because it can be used to explain climate change of any length or intensity. However, no major *long-term* variations in the total intensity of solar radiation have yet been measured. Such measurements were not even possible until satellite technology became available. Now that we can measure solar output, we still need many decades of records before we will begin to sense how variable (or invariable) the Sun's energy output really is.

> An increase in solar output would cause the atmosphere to warm, but no major *long-term* variations in the total intensity of solar radiation have yet been measured.

Other hypotheses for climate change based on solar variability are related to sunspot cycles. The most conspicuous and best-known features on the surface of the Sun are dark blemishes called **sunspots** (Figure 14.11), which are vast magnetic storms that extend from the Sun's surface deep into the interior. Moreover, these sunspots are associated with the ejection of huge masses of particles into space that, on reaching Earth's upper atmosphere, interact with gases there to produce auroral displays (see Figure 1.23).

Figure 14.11 Sunspots

Both images show sunspot activity at the same location on the solar disk at the same time on March 5, 2012, using two different instruments from NASA's Solar Dynamics Observatory.



A. The black spots surrounded by deep orange is a sunspot region where magnetic activity is extremely intense.

B. The looping lines connect sunspots, a type of solar storm that enhances solar output.

Sunspots occur in cycles, with the number of spots reaching a maximum about every 11 years. During periods of maximum sunspot activity, the Sun emits slightly more energy than during sunspot minimums. Based on measurements from space that began in 1978, the variation during an 11-year cycle is about 0.1 percent. It appears that this change in solar output is too small to have any appreciable effect on global temperatures.

However, there is a possibility that longer-term variations in solar output may affect climates on Earth. For example, the span between 1645 and 1715 was a period known as the *Maunder minimum*, during which sunspots were largely absent. This period of missing sunspots closely corresponds with a period in climate history known as the *Little Ice Age*, an especially cold period in Europe. For some scientists, this correlation suggests that a reduction in the Sun's output was likely responsible at least in part for this cold episode.

You might have wondered . . .

Is there a connection between changes in the Sun's brightness and recent evidence of climate change?

Based on recent satellite data, the answer is no. The scientists who carried out this detailed analysis state that the variations in solar brightness measured since 1978, which is as far back as these measurements go, are too small to have contributed appreciably to accelerated warming over the past 30 years.

Volcanic Activity and Climate Change

Volcanic eruptions are regarded as another plausible explanation for some aspects of climate variability. Explosive eruptions emit huge quantities of gases and fine-grained debris into the atmosphere (Figure 14.12). The largest eruptions are sufficiently powerful to inject material high into the stratosphere, where it spreads around the globe and remains suspended for many months or even years.

Figure 14.12 Eruption of volcanic ash and gases from Mount Bromo, 2011, on the island of Java in Indonesia.

The basic premise is that the suspended volcanic material will reflect or scatter a portion of the incoming solar radiation, which in turn will lower temperatures in the troposphere. Perhaps the most notable cool period linked to a volcanic event is the "year without a summer" that followed the 1815 eruption of Mount Tambora, Indonesia, the largest of modern times. During April 7–12, 1815, this volcano violently expelled more than 100 cubic kilometers (24 cubic miles) of volcanic debris. The impact of these tiny suspended particles is believed to have been widespread in the Northern Hemisphere. From May through September 1816, an unprecedented series of cold spells affected the northeastern United States and adjacent portions of Canada. The region experienced heavy snow in June and frost in July and August. Much of Western Europe also experienced abnormal cold.

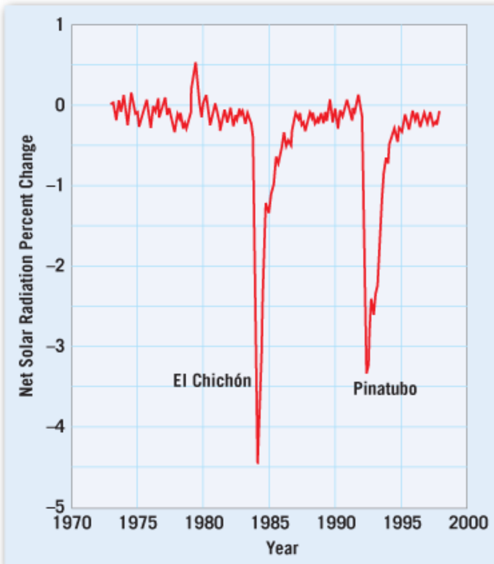
El Chichón and Mount Pinatubo

Two more recent volcanic events have provided considerable data and insight regarding the impact of volcanoes on global temperatures. The eruptions of the Mexican volcano El Chichón in 1982 and Mount Pinatubo in the Philippines in 1991 gave scientists opportunities to study the atmospheric effects of volcanic eruptions with the aid of more sophisticated technology than had been available in the past. Satellite images and remote-sensing instruments allowed scientists to closely monitor the effects of the clouds of gases and ash that these volcanoes emitted.

Two years of monitoring and studies following the 1982 El Chichón eruption indicated that it had a cooling effect on global mean temperature, on the order of about 0.5°C (0.9°F). The historic eruption, although not particularly explosive, emitted huge quantities of sulfur dioxide high into the atmosphere. This gas combines with water vapor in the stratosphere to produce a dense cloud of tiny sulfuric acid particles. These aerosols take several years to settle out completely. Like volcanic ash, tiny sulfuric acid droplets lower the troposphere's mean temperature because they reflect solar radiation back to space (Figure 14.13).

Figure 14.13 **Volcanic debris reducing sunlight at Earth's surface**

The eruption of El Chichón and Mount Pinatubo clearly caused a temporary drop in solar radiation reaching Earth's surface.



Net solar radiation at Hawaii's Mauna Loa Observatory relative to 1970 (zero on the graph). The eruptions of El Chichón and Mt. Pinatubo clearly caused temporary drops in solar radiation reaching the surface.

We now understand that volcanic debris suspended in the stratosphere for a year or more is composed largely of sulfuric acid droplets and not of volcanic ash, as was once thought. Thus, the volume of volcanic ash emitted during an explosive event is not an accurate criterion for predicting the global atmospheric effects of an eruption.

The Impact of Volcanic Eruptions

The impact on climate of a single volcanic eruption, as just described for El Chichón, is relatively small and short-lived. The graph in Figure 14.13 reinforces this point. If volcanism is to have a pronounced impact over an extended period, either a much larger volcanic eruption or many eruptions rich in sulfur dioxide and closely spaced in time must occur. Events like these could load the stratosphere with enough gases and volcanic ash to significantly diminish the amount of solar radiation reaching the surface.

Although no such period of explosive volcanism is known to have occurred in historic times, we know that eruptions on this scale have occurred at various times in the geologic past. The eruption that produced the landscape of Yellowstone National Park, 630,000 years ago, emitted more than 100 times the volcanic ash and gas as the eruption of Mount Pinatubo in 1991. This catastrophic eruption sent showers of debris as far as the Gulf of Mexico. Eruptions on the scale of the Yellowstone volcanism and other massive events would have clearly had a greater impact on past climate (Box 14.1).

Box 14.1

Volcanism and Climate Change in the Geologic Past

The Cretaceous period, the last period of the Mesozoic era, is often called the Age of Dinosaurs. It began about 145 million years ago and ended about 65 million years ago, with the extinction of the dinosaurs and many other life-forms.

The Cretaceous climate was among the warmest in Earth's long history. Dinosaur fossils of that period have been discovered north of the Arctic Circle. Tropical forests existed in Greenland and Antarctica, and deposits of peat that would eventually form widespread coal beds accumulated at high latitudes. Sea level was as much as 200 meters (650 feet) higher than today, indicating that there were no polar ice sheets.

What was the cause of the unusually warm climates of the Cretaceous period? Among the factors thought to have contributed was an enhanced greenhouse effect due to increased carbon dioxide in the atmosphere. Geologists have concluded that the probable source of the CO_2 that aided Cretaceous warming was volcanic activity. Carbon dioxide is one of the gases emitted during volcanism, and there is considerable geologic evidence that there was an unusually high rate of volcanic activity during the Cretaceous. Several huge oceanic lava plateaus were produced on the floor of the western Pacific during this span. These vast features were associated with hot spots, zones where mobile plumes of molten material rise to the surface from deep in Earth's interior. Massive outpourings of lava over millions of years would have been accompanied by the release of huge quantities of CO_2, which in turn would have enhanced the atmospheric greenhouse effect. *Thus, the warmth that characterized the Cretaceous may have had its origins deep in Earth's interior.*

> The link between the extraordinary period of volcanism and warming during the Cretaceous illustrates that volcanism can have a dramatic effect on global climates.

Evidence for this extraordinarily warm period is the quantity and types of phytoplankton (tiny, mostly microscopic plants, such as algae) and other life-forms that inhabited the Cretaceous oceans. The explosion of marine life is reflected in the widespread chalk formations associated with this period of Earth's history (Figure 14.A). These massive deposits consist mainly of the calcium carbonate ($CaCO_3$) shells of microscopic marine organisms. In addition, some of the world's most important oil and gas fields are in marine sediments of the Cretaceous, a consequence of the greater abundance of marine life during that period of warming. (Oil and gas originate from the alteration of biological remains—chiefly phytoplankton.)

Figure 14.A White Cliffs of Dover

These famous chalk deposits along the coast of England are composed largely of tiny shells of marine organisms and are associated with the expansion of marine life that occurred during the exceptional warmth of the Cretaceous period.

The link between the extraordinary period of volcanism and warming during the Cretaceous illustrates that volcanism can have a dramatic effect on global climates. Furthermore, processes originating deep in Earth’s interior are connected directly or indirectly to the atmosphere, the oceans, and the biosphere.

Apply What You Know

1. What is thought to be the cause of global warming during the Cretaceous period?
2. What do we see in the present-day landscape that is linked to climate during the Cretaceous period?

> Large historical volcanic eruptions have caused only temporary climate change on local and regional scales, but more explosive eruptions in the past have altered global climate more dramatically.

You might have wondered . . .

Could a meteorite colliding with Earth cause the climate to change?

Yes, it is possible. In fact, the most strongly supported hypothesis for the extinction of dinosaurs and many other organisms about 65 million years ago is related to such an event. When a large (about 10 kilometers in diameter) meteorite struck Earth, huge quantities of debris were blasted high into the atmosphere. For a period of as much as two years, the encircling dust cloud greatly restricted the amount of light reaching Earth's surface. Without sufficient sunlight for photosynthesis, delicate food chains collapsed. When the sunlight returned, more than half of the species on Earth, including the dinosaurs and many marine organisms, had become extinct.

Concept Checks 14.3

- How does the theory of plate tectonics help us understand the cause of ice ages?
- List and briefly describe the three variations in Earth's orbit that are thought to cause global temperatures to vary.
- How does solar output change as sunspot numbers change?
- Describe and briefly explain the effect of the El Chichón eruption on global temperatures.

14.4 Human Impacts on Global Climate

LO 4 Summarize the nature and cause of the atmosphere's changing composition since about 1750. Describe the climate's response.

Having examined *natural causes* of climate change, we now shift our focus to how *humans* contribute to global climate change. Human influence on global climate did not just begin with the onset of the modern industrial age. There is evidence that people have been modifying the environment over extensive areas for thousands of years. Both the use of fire and the overgrazing of lands in semi-arid regions by domesticated animals have reduced the abundance and distribution of vegetation. By altering ground cover, humans have modified such important climatic factors as surface albedo and evaporation rates.

However, the most significant impact humans have had on climate is the recent addition of carbon dioxide and other greenhouse gases into the atmosphere. A secondary impact is the addition of human-generated aerosols to the atmosphere.

Rising Carbon Dioxide Levels

In Chapter 1, you learned that carbon dioxide (CO_2) represents only about 0.0400 percent (400 parts per million) of the gases that make up clean, dry air. Nevertheless, it is a significant component meteorologically. Carbon dioxide is influential because it is transparent to incoming short-wavelength solar radiation, but it is not transparent to the longer-wavelength outgoing terrestrial radiation. A portion of the energy leaving Earth's surface is absorbed by atmospheric CO_2. This energy is subsequently re-emitted, part of it back toward the surface, thereby keeping the air near the ground warmer than it would be without CO_2. Thus, along with water vapor, carbon dioxide is largely responsible for the *greenhouse effect* of the atmosphere. Carbon dioxide is an important heat absorber, and it follows logically that any change in the air's CO_2 content could alter temperatures in the lower atmosphere.

> Carbon dioxide is an important heat absorber, and any change in the air's CO_2 content could alter temperatures in the lower atmosphere.

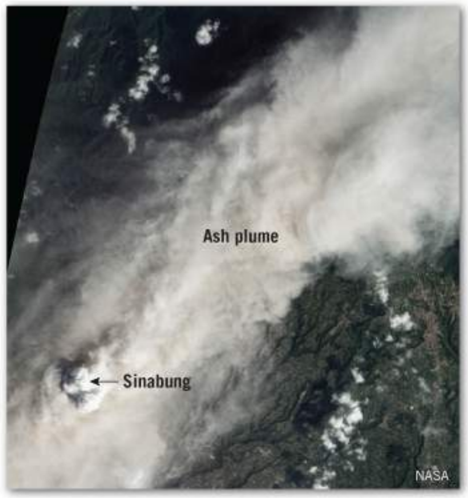
Industrialization of the past two centuries has been fueled by burning fossil fuels: coal, natural gas, and petroleum (see Figure 13.7). Combustion of these fuels has added large quantities of carbon dioxide to the atmosphere. The clearing of forests also contributes substantially because CO_2 is released when vegetation is burned or decays (Figure 14.14). Deforestation is particularly pronounced in the tropics, where vast tracts are cleared for ranching and agriculture or are subjected to commercial logging operations. All major tropical forests—including those in South America, Africa, and Southeast Asia—are disappearing. According to United Nations estimates, more than 10 million hectares (25 million acres) of tropical forest were permanently destroyed *each year* during the decades of the 1990s and 2000s.

Figure 14.14 **Tropical deforestation**

Clearing of the tropical rain forest is a significant source of carbon dioxide. Fires are frequently used to clear the land.

Eye on the Atmosphere 14.1

This satellite image shows an extensive plume of ash from an explosive volcanic eruption of Indonesia's Sinabung volcano on January 16, 2014.



Apply What You Know

1. How might the volcanic ash from this eruption influence air temperatures?
2. Would this effect likely be long lasting—perhaps for years? Explain.
3. What "invisible" volcanic emission might have a greater effect than the volcanic ash?

Increasing levels of CO_2 are attributed mainly to the use of fossil fuels and deforestation.

Some of the excess CO_2 is taken up by plants or is dissolved in the ocean, but an estimated 45 percent remains in the atmosphere. A graphic record of changes in atmospheric CO_2 extending back 800,000 years was provided earlier in Figure 14.5B. Over this long span, natural fluctuations caused CO_2 concentrations to vary from about 180 ppm to 300 ppm. However, by 2016 the level was about 40 percent higher than the levels prior to the Industrial Revolution. Even more alarming is that over the past several decades, there has been an acceleration of the annual rate at which atmospheric carbon dioxide concentrations have increased.

The Role of Trace Gases

Carbon dioxide is not the only gas contributing to a global increase in temperature. In recent years, atmospheric scientists have come to realize that human industrial and agricultural activities are causing a buildup of several trace gases that also play significant roles in warming the atmosphere. The substances are called **trace gases** because their concentrations are so much lower than the concentration of carbon dioxide. The most important trace gases are methane (CH_4) and nitrous oxide (N_2O). These gases absorb wavelengths of outgoing radiation from Earth that would otherwise escape into space. Although individually their impact is modest, taken together trace gases play a significant role in warming the troposphere.

You might have wondered . . .

What is the Intergovernmental Panel on Climate Change?

The Intergovernmental Panel on Climate Change (IPCC) was established by the World Meteorological Organization and the United Nations Environment Programme in 1988 to assess scientific, technical, and socioeconomic information relevant to an understanding of human-induced climate change. The IPCC provides periodic reports regarding the state of knowledge about the causes and effects of climate change. These assessment reports are the basis for the Paris Climate Accord, which calls for countries to take measures to mitigate climate change.

Methane

Although present in much smaller amounts than CO_2, methane's significance is greater than its relatively small concentration would indicate. The reason is that methane is about 20 times more effective than CO_2 at absorbing infrared radiation emitted by Earth.

Methane is produced by *anaerobic* bacteria in wet places where oxygen is scarce. (*Anaerobic* means "without air," specifically oxygen.) Such places include swamps, bogs, wetlands, and the guts of termites and grazing animals such as cattle and sheep. Methane is also generated in flooded paddy fields ("artificial swamps") used for growing rice.

The increase in the concentration of methane in the atmosphere has been in sync with the growth in human population. This relationship reflects the close link between methane formation and agriculture. As population increases, so do the number of cattle and rice paddies. Mining of coal and drilling for oil and natural gas are other sources because methane is released during these activities.

Nitrous Oxide

Sometimes called "laughing gas," nitrous oxide is also building in the atmosphere, although not as rapidly as methane. The increase results primarily from agricultural activity. When farmers use nitrogen fertilizers to boost crop yield, some of the nitrogen enters the air as nitrous oxide. This gas is also produced by high-temperature combustion of fossil fuels. Although the annual release into the atmosphere is small, the lifetime of a nitrous oxide molecule in the atmosphere is about 150 years! If nitrogen fertilizer and fossil fuel use grow at projected rates, nitrous oxide's contribution to greenhouse warming may approach half that of methane.

> Methane and nitrous oxide are greenhouse gases that occur both naturally and from human sources.

A Combined Effect

Carbon dioxide is clearly the most important single cause for the projected global greenhouse warming. When the effects of all human-generated greenhouse gases other than CO_2 are added together and projected into the future, their collective impact significantly increases the impact of CO_2 alone.

Eye on the Atmosphere 14.2

This satellite image from August 2007 shows the effects of tropical deforestation in a portion of the Amazon basin in western Brazil. Intact forest is dark green, whereas cleared areas are tan (bare ground) or light green (crops and pasture). Notice the relatively dense smoke in the left center of the image.

Apply What You Know

1. How does the destruction of tropical forests change the composition of the atmosphere?
2. Describe the effect that tropical deforestation has on global warming.

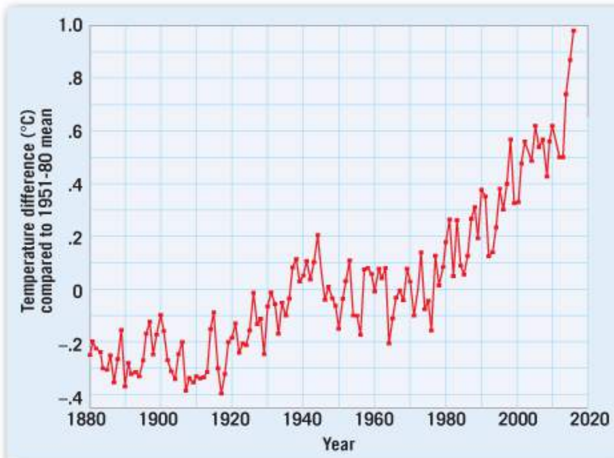
The Atmosphere's Response

Given the increase in the atmosphere's greenhouse gas content, have global temperatures actually increased? The answer is yes. According to a 2014 report by the Intergovernmental Panel on Climate Change (IPCC), "Warming of the climate system is unequivocal, and many of the observed changes are unprecedented. . . . The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, and sea level has risen."* Most of the observed increase in global average temperatures since the mid-twentieth century is *extremely likely* because of the observed increase in human-generated greenhouse gas concentrations.

Globally, average temperatures in 2016 were about 1.0°C (1.8°F) warmer than the mid-twentieth century mean. This upward trend in surface temperatures is shown in Figure 14.15. With the exception of 1998, the 10 warmest years have all occurred since 2000, with 2016 ranking as the warmest year since modern record keeping began in 1880.

Figure 14.15 **Graph illustrating the trend in global temperatures, 1880–2016**

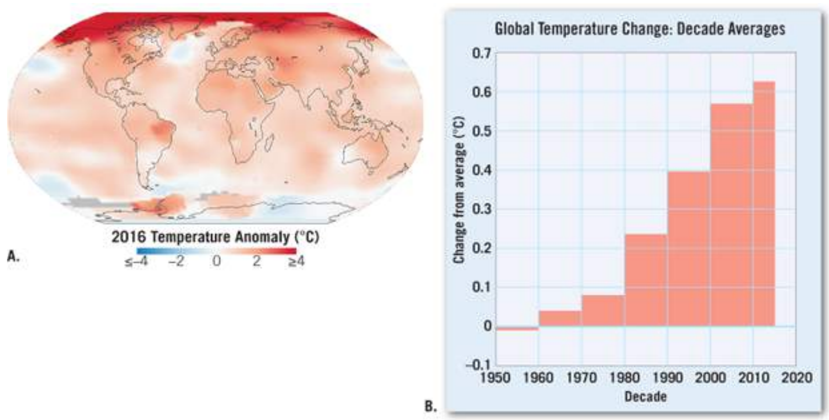
With the exception of 1998, 10 of the warmest years in this 134-year temperature record have occurred since 2000.



Weather patterns and other natural cycles cause fluctuations in average temperatures from year to year, especially on regional and local levels. For example, while the globe experienced record high temperatures in 2016, the continental United States, Iceland, and parts of China experienced unusually cold January weather. Yet it was a record warm year for North America and the third-warmest year on record for Asia. Regardless of regional and seasonal differences in any year, increases in greenhouse gas levels are causing a long-term rise in global temperatures (Figure 14.16A). Although each calendar year will not necessarily be warmer than the one before, scientists expect each decade to be warmer than the previous one. An examination of the decade-by-decade temperature trend in Figure 14.16B bears this out.

Figure 14.16 Decade-by-decade temperature trend

A. The world map shows how the average temperatures in 2016 deviated from the mean for the 1951–1980 base period. **B.** The decade-by-decade temperature trend since 1950—each decade has been warmer than the previous one. Continued increases in the atmosphere's greenhouse gas levels are driving a long-term increase in global temperatures.



Watch Animation: Global Warming

> The atmosphere's response to an increase in greenhouse gases is an increase in temperature, although not every location warms equally.

How Aerosols Influence Climate

Global climate is also affected by human activities that contribute to the atmosphere's aerosol content. Recall that *aerosols* are tiny, often microscopic, liquid and solid particles suspended in the air. Unlike cloud droplets, aerosols are present even in relatively dry air. Natural sources are numerous and include such phenomena as wildfires, dust storms, breaking waves, and volcanoes, while most human-generated aerosols come from the sulfur dioxide emitted during the combustion of fossil fuels and from burning of vegetation to clear agricultural land. Chemical reactions in the atmosphere convert the sulfur dioxide into sulfate aerosols, the same material that produces acid precipitation (see Chapter 13).

How do aerosols affect climate? Most aerosols act directly by reflecting sunlight back to space and indirectly by making clouds "brighter" reflectors. The second effect relates to the fact that many aerosols (such as those composed of salt or sulfuric acid) attract water and thus are especially effective as cloud condensation nuclei. The large quantity of aerosols produced by human activities, especially industrial emissions, triggers an increase in the number of cloud droplets that form within a cloud. A greater number of small droplets increases the cloud's brightness, causing more sunlight to be reflected back to space.

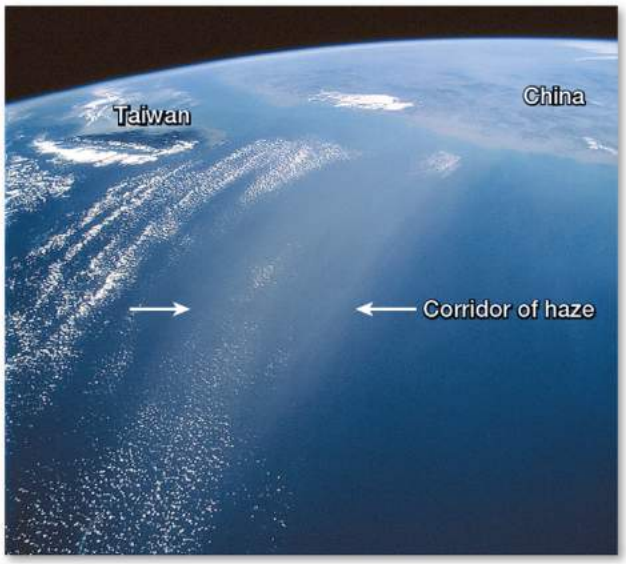
One category of aerosols, called **black carbon**, is soot generated by combustion processes and fires. Unlike other aerosols, black carbon warms the atmosphere because it is an effective absorber of incoming solar radiation. When deposited on snow and ice, black carbon also reduces surface albedo, thus increasing the amount of light absorbed. Nevertheless, despite the warming effect of black carbon, the overall effect of atmospheric aerosols is to cool Earth.

> The net effect of aerosols is to cool the atmosphere, which offsets some of the global warming.

Studies indicate that the cooling effect of human-generated aerosols offsets a portion of the global warming caused by the growing quantities of greenhouse gases in the atmosphere. The magnitude and extent of the cooling effect of aerosols are uncertain. It is important to point out, however, that there are some significant differences between global warming by greenhouse gases and aerosol cooling. After being emitted, carbon dioxide and trace gases remain in the atmosphere and influence climate for many decades. By contrast, aerosols released into the troposphere remain there for only a few days or, at most, a few weeks before they are "washed out" by precipitation, limiting their effect on today's climate. Because of their short lifetime in the troposphere, aerosols are distributed unevenly over the globe. As expected, human-generated aerosols are concentrated near the areas that produce them, namely industrialized regions that burn fossil fuels and places where vegetation is burned (Figure 14.17).

Figure 14.17 Aerosol haze

Human-generated aerosols are concentrated near areas that produce them. Because most aerosols reduce the amount of solar energy available to the climate system, they have a net cooling effect. This satellite image shows a dense blanket of pollution moving away from the coast of China. The plume is about 200 kilometers (125 miles) wide and more than 600 kilometers (375 miles) long.



Concept Checks 14.4

- Why has the CO_2 level of the atmosphere been increasing over the past 200 years? Aside from CO_2, what trace gases are contributing to global temperature change?
- How are temperatures in the lower atmosphere likely to change as greenhouse gas levels continue to increase?
- List the main sources of human-generated aerosols, and describe their net effect on atmospheric temperatures.

* IPCC, "Observed Changes and Their Causes," *in Climate Change 2014 Synthesis Report*.

14.5 Predicting Future Climate Change

LO 5 Contrast positive- and negative-feedback mechanisms and provide examples of each.

Climate is a very complex interactive system. When any component of the climate system is altered, scientists must consider various possible responses called **feedback mechanisms**. Feedback mechanisms complicate climate-modeling efforts and add greater uncertainty to climate predictions. Therefore, increases in temperature and other changes in climate expected by the end of this century are difficult to predict.

Types of Feedback Mechanisms

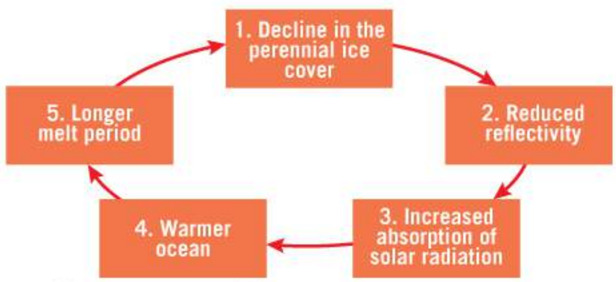
One significant feedback mechanism associated with global warming is that warmer ocean surface temperatures result in increased evaporation rates. This, in turn, increases the amount of water vapor in the atmosphere. Remember that water vapor is a more powerful absorber of radiation emitted by Earth than carbon dioxide. Therefore, with more water vapor in the air, the temperature increase caused by greenhouse gases is reinforced. Because this effect enhances the initial change, it is called a **positive-feedback mechanism**.

Another well-understood positive-feedback mechanism relates to the extent of Arctic sea ice (Figure 14.18A) and continental ice sheets. Because ice reflects a much larger percentage of incoming solar radiation than open water or land, the melting of ice replaces a highly reflective surface with a relatively dark surface (Figure 14.18B). The result is a substantial increase in the solar energy absorbed at the surface, which leads to higher surface temperatures and therefore even less ice cover.

Figure 14.18 Melting of sea ice is a positive-feedback mechanism

A. Polar bear and her cubs waking across Arctic sea ice at the start of the spring melt. **B.** A reduction in sea ice acts as a positive-feedback mechanism because surface albedo decreases, and the amount of energy absorbed at the surface increases.

A. Arctic sea ice



B. Positive-feedback mechanism

The climate-feedback mechanisms discussed thus far magnify the temperature increases caused by the buildup of greenhouse gases. However, other effects are classified as **negative-feedback mechanisms** because they produce results that are just the opposite of the initial change and tend to offset it.

> Positive-feedback mechanisms reinforce the initial change, while negative-feedback mechanisms weaken the initial change.

For example, an increase in the rate of evaporation results in an increase in cloud cover because of the atmosphere′s higher moisture content. Most clouds are good reflectors of incoming solar radiation. At the same time, however, they are also good absorbers and emitters of long-wavelength radiation emitted by Earth. Consequently, clouds produce two opposite effects. On the one hand, they are negative-feedback mechanisms because they increase Earth′s albedo and thus diminish the amount of solar energy available to heat the atmosphere. On the other hand, clouds act to warm the lower atmosphere by absorbing long-wavelength terrestrial radiation that would otherwise be lost to space. In the latter case, they serve as positive-feedback mechanisms.

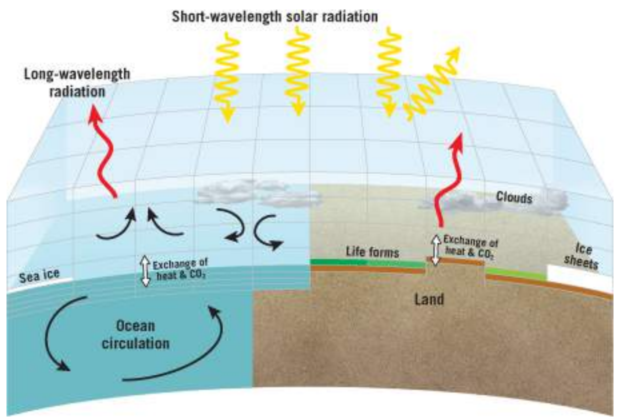
Which effect, if either, is stronger? Recent studies suggest that this question is more complex than first thought. Whether clouds are a net positive- or negative-feedback mechanism depends mainly on the type of clouds. For example, a blanket of thin stratus clouds increases albedo more than it absorbs outgoing terrestrial radiation, so thin stratus clouds tend to have a cooling effect. By comparison, a thick cumulus cloud bank absorbs a greater amount of outgoing terrestrial radiation than the amount of incoming radiation it reflects toward space, thus leading to warming. The combined effect that clouds have on climate change isn′t fully understood, making it one of the greatest obstacles to modeling future climate change.

Computer Models of Climate Change: Important yet Imperfect Tools

Because predictions of how the climate might change in the future can't be tested by direct experimentation in a laboratory, scientists rely heavily on computer models of how our planet's climate system works. If we understand the climate system correctly and construct the model appropriately, then the behavior of the model climate system should mimic the behavior of Earth's climate system.

Comprehensive state-of-the-science climate simulation models are among the basic tools used to develop possible climate-change scenarios. Called **general circulation models (GCMs)**, they are based on fundamental laws of physics and chemistry and incorporate human and biological interactions. GCMs use a three-dimensional grid of "boxes" that divide the atmosphere and the ocean and land surfaces into blocks (Figure 14.19). The more boxes the model uses, the more closely it can approximate the real Earth, but also the more computing power the model requires to do the calculations. GCMs are used to simulate variables, including the amount of solar radiation striking the surface, the extent of cloud cover, changes in greenhouse gas concentrations, variations in the extent of sea ice, and many other parameters.

Figure 14.19 Computer models of the climate system are used to predict future climate trends



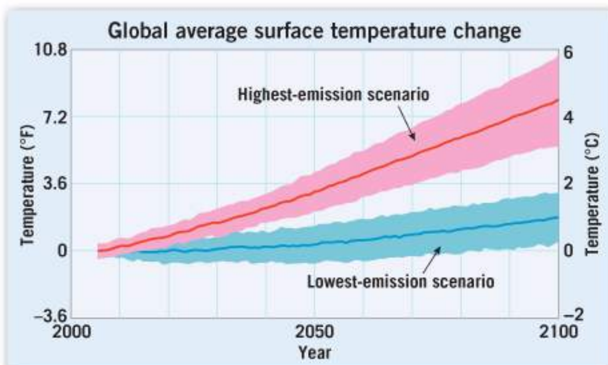
> General circulation models (GCMs) are computer models that simulate how the climate system works.

What factors influence the accuracy of climate models? Clearly, mathematical models are *simplified* versions of the real Earth and cannot capture its full complexity. Moreover, computer models used to simulate future climate change must make many assumptions that significantly influence predictions. They must consider a wide range of possible changes in population, economic growth, fossil fuel consumption, technological development, improvements in energy efficiency, possible positive and negative feedbacks, and much more.

Despite many obstacles, our ability to use supercomputers to simulate climate continues to improve. Although today's models are far from infallible, they are powerful tools for understanding what Earth's future climate might be like.

What do computer models tell us about the future? Projections for the years ahead depend, in part, on the quantities of emitted greenhouse gases. Figure 14.20 shows the IPCC report's best estimates of global warming for two different emission scenarios. The highest-emission scenario estimates that if the pre-industrial level of carbon dioxide were to double—from 280 ppm to 560 ppm—the *likely* temperature increase would be about 4.5°C (8.1°F) by the end of the century. Values higher than 4.5°C (8.1°F) are also possible. By contrast, under the lowest-emission scenario, surface air temperatures would rise only about 1.5°C (2.7°F) above current levels (Figure 14.20). The report goes on to say that a temperature increase of less than 1.5°C (2.7°F) is *very unlikely*.

Figure 14.20 Projected temperature changes based on two emission scenarios



Watch Video: Temperatures and Agriculture

Sophisticated computer models also show that the warming of the lower atmosphere caused by CO_2 and trace gases will not be the same everywhere. Rather, the temperature response in polar regions could be two to three times greater than the global average. One reason is the fact that the polar troposphere is very stable, which suppresses vertical mixing and thus limits the amount of surface heat transferred upward. In addition, an expected reduction in sea ice would contribute to the greater temperature increase. This topic will be explored more fully in the next section.

Concept Checks 14.5

- Distinguish between positive- and negative-feedback mechanisms, and provide an example of each.
- What factors influence the accuracy of computer models of climate?

14.6 Some Consequences of Climate Change

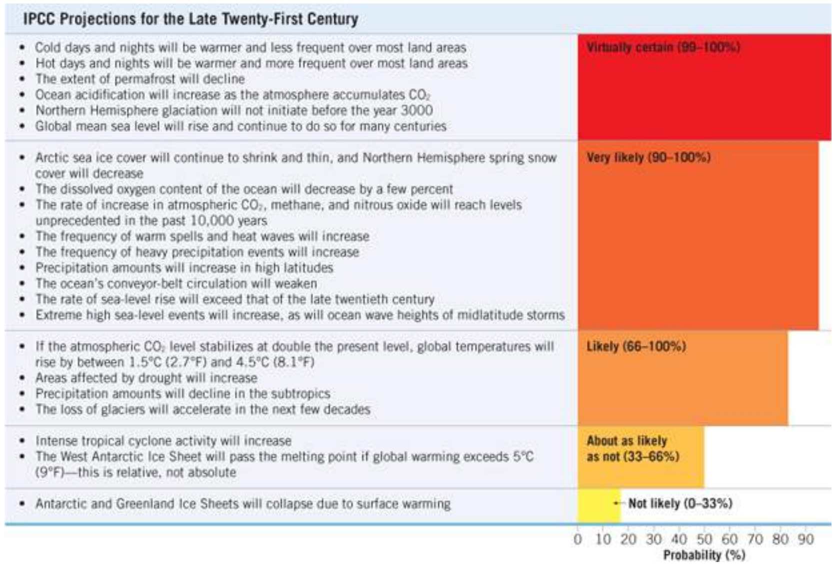
LO 6 Suggest several likely consequences of global climate change.

Because the climate system is complex, predicting the occurrence of specific effects in particular places is speculative—it is not yet possible to pinpoint such changes. Nevertheless, plausible scenarios exist that predict larger-scale changes to global climate by the end of this century.

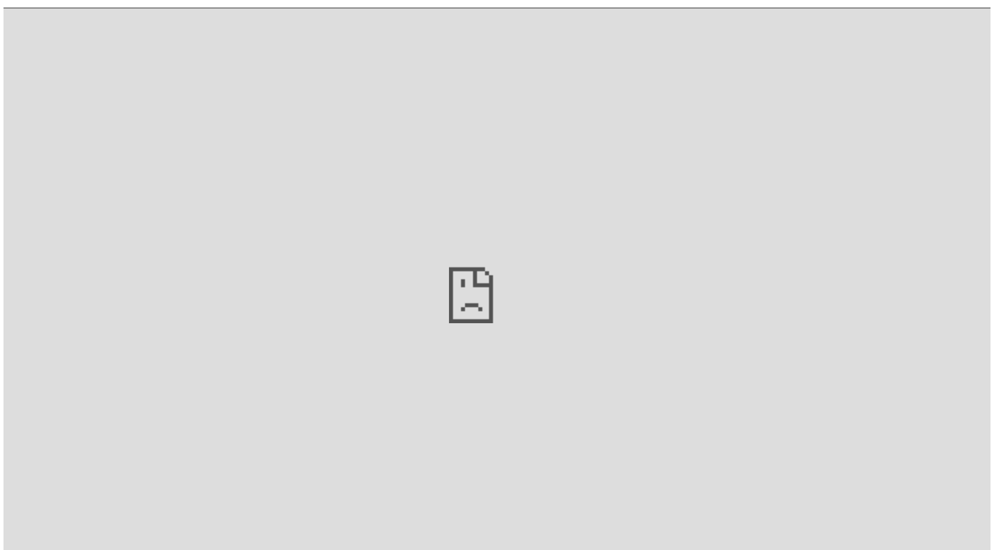
As noted, the magnitude of the temperature increase will not be the same everywhere. The temperature rise will probably be smallest in the tropics and increase toward the poles. As for precipitation, models indicate that some regions will experience significantly more precipitation and runoff. However, other parts of the world will experience a decrease in runoff due to reduced precipitation or to greater evaporation caused by higher temperatures.

Figure 14.21 summarizes some of the most likely effects and their possible consequences. The figure also provides the IPCC′s estimate of the probability of each effect. Levels of confidence for these projections vary from *likely* (66 to 90 percent probability) to *very likely* (90 to 99 percent probability) to *virtually certain* (greater than 99 percent probability).

Figure 14.21 Summary of the likely climate changes and their predicted impacts



Watch Video: Global Warming Predictions



Sea-Level Rise

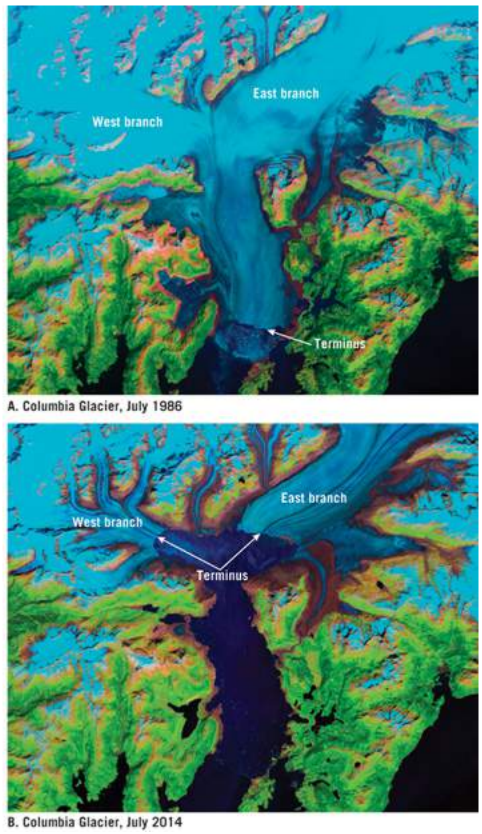
One significant impact of human-induced climate change is a rise in sea level. As this occurs, coastal cities, wetlands, and low-lying islands could be threatened with more frequent flooding. In addition, increased shoreline erosion and saltwater encroachment into coastal rivers and aquifers that supply fresh water to nearby cities is expected.

How is a warmer atmosphere related to a rise in sea level? One important factor is thermal expansion of the uppermost layer of the global ocean. Higher air temperatures warm the adjacent upper layers of the ocean, which in turn causes the water volume to expand and sea level to rise.

A second factor contributing to global sea-level rise is the melting of glacial ice. With few exceptions, glaciers around the world have been retreating at unprecedented rates over the past century (Figure 14.22). A satellite study spanning 20 years showed that the mass of the Greenland and Antarctic ice sheets dropped an average of 475 gigatons per year. (A gigaton is 1 billion metric tons.) That is enough water to raise sea level 1.5 millimeters (0.05 inch) *per year*. Of greater concern is that the loss of glacial ice mass occurred at an accelerating rate during the study period.

Figure 14.22 Two false-color satellite images of Columbia Glacier taken about 28 years apart

The retreat and thinning of the Columbia Glacier over that short time span, geologically speaking, has been significant.



> Sea level is expected to rise because of thermal expansion of ocean water and the melting of sea ice and continental ice sheets.

Mountain glaciers are also shrinking at alarming rates. For example, in 1850, there were about 150 documented glaciers in Glacier National Park, Montana. Today there are only 25 ice bodies in this area of the Rocky Mountains, not all of them active glaciers. Based on current estimates, Glacier National Park will be glacier free within the next few decades.

You might have wondered . . .

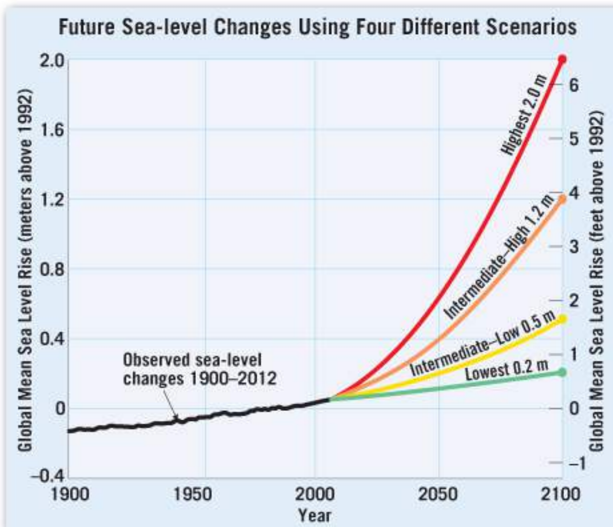
What are scenarios, and why are they used?

A scenario is an example of what might happen under a particular set of assumptions. Using scenarios is a way of examining questions about an uncertain future. For example, future trends in fossil fuel use and other human activities are uncertain. Therefore, scientists have developed a range of scenarios for how climate may change based on a wide range of possibilities for these variables.

Research indicates that sea level has risen about 25 centimeters (9.75 inches) since 1870, with the rate of sea-level rise accelerating in recent years. As Figure 14.23 indicates, the estimates of future sea-level rise are uncertain. The four scenarios depicted on the graph represent estimates based on different degrees of ocean warming and ice sheet loss and range from 0.2 meter (8 inches) to 2 meters (6.6 feet). The lowest scenario is an extrapolation of the annual rate of sea-level rise that occurred between 1870 and 2000 (1.7 millimeters/year). However, when the rate of sea-level rise for the period 1993 to 2012 is examined, the annual change is 3.17 millimeters/year. Such data show that there is a reasonable chance that sea level will rise considerably more than the lowest scenario indicates.

Figure 14.23 Changing sea level

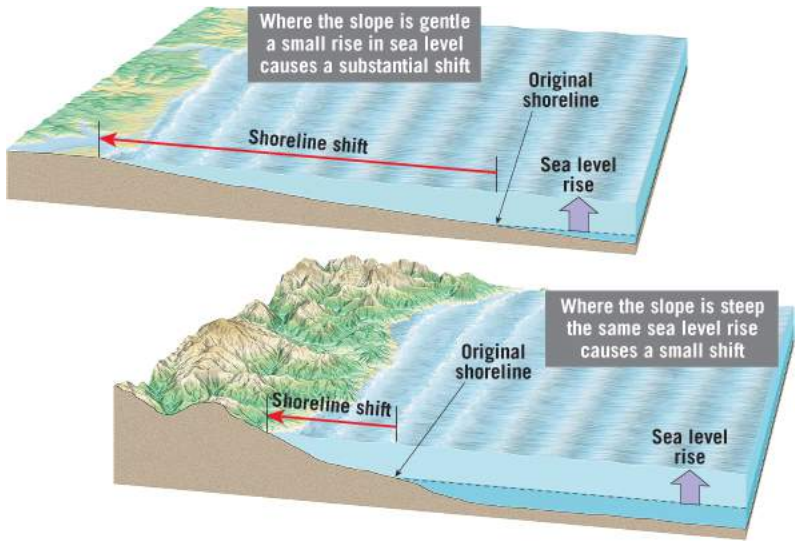
This graph shows changes in sea level between 1900 and 2012 and projections to 2100 using four different scenarios. Currently the highest and lowest projections are considered to be extremely unlikely. The greatest uncertainty surrounding estimates is the rate and magnitude of ice sheet loss from Greenland and Antarctica. Zero on the graph represents mean sea level in 1992.



Even modest rises in sea level along a *gently* sloping shoreline, such as the Atlantic and Gulf coasts of the United States, will lead to significant erosion and severe permanent inland flooding (Figure 14.24). If this happens, many beaches and wetlands will be eliminated, and heavily populated coastal areas will be inundated. Low-lying and densely populated places such as Bangladesh and the small island nations such as the Maldives are especially vulnerable. The average elevation in the Maldives is 1.5 meters (less than 5 feet), and its highest point is just 2.4 meters (less than 8 feet) above sea level.

Smartfigure 14.24 **Sea-level rise and shoreline slope**

The slope of the shoreline is critical to determining the degree to which sea-level changeswill affect it. As sea level gradually rises, the shoreline retreats, and structures that were once thought to be safe from wave attack become vulnerable.



Watch **SmartFigure: Shoreline Shift**

Watch **Video: Climate Change Through Native Alaskan Eyes**

The Changing Arctic

The effects of climate change are most pronounced in the high latitudes of the Northern Hemisphere. For more than 30 years, the extent and thickness of sea ice, mountain glaciers, and continental ice sheets have been rapidly declining. Another sign that the Arctic is rapidly warming is related to plant growth. A 2013 study showed that the type and growth of vegetation at northern latitudes now resembles that which characterized areas 4° to 6° of latitude farther south as recently as 1982—a distance of 400 to 700 kilometers (250 to 430 miles). One researcher characterized the finding this way: "It's like Winnipeg, Manitoba, moving to Minneapolis–St. Paul in only 30 years."

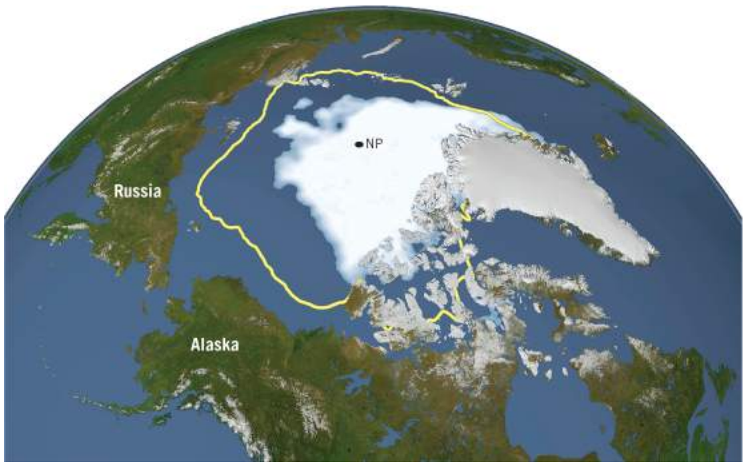
Arctic Sea Ice

Climate models generally assert that one of the strongest signals of climate change should be a loss of sea ice in the Arctic. Sea ice grows in extent and thickness over the Arctic Ocean when temperatures drop to below freezing (about −1°C because the water is salty) during the fall and winter. It can be as thick as 6 meters (20 feet) and is usually thickest in areas where it makes contact with land and stays there year-round. In the summer, as temperatures climb, Arctic sea ice decreases in extent and thickness, often breaking into large slabs near their margins (see Figure 14.18A).

The image in Figure 14.25 compares the average Arctic sea ice extent for September 2016 to the long-term average for the period 1979–2000. September 2016 ties the record for the second lowest sea ice extent. (September represents the end of the melt period, when the area covered by sea ice is at a minimum.) Not only is the area covered by sea ice declining, but the remaining sea ice has become thinner, making it more vulnerable to further melting.

Figure 14.25 **Tracking sea ice changes**

Sea ice is frozen seawater. In winter, the Arctic Ocean is completely covered with ice. In summer, a portion of the ice melts. This map shows the extent of sea ice in early September 2012 compared to the average extent (yellow line) for the period 1979 to 2000. The lowest annual sea ice extent occurred in 2016. The sea ice that does not melt in summer is getting thinner.



The Arctic's sea ice maximum extent has also dropped by an average of 2.8 percent per decade since 1979, the year satellites started to continuously measure sea ice. In fact, the sea ice maximum in 2016 was the lowest on record. Models that best match historical trends project that Arctic waters may be virtually ice free during the summer sometime in the 2030s. As noted earlier, a reduction in sea ice represents a positive-feedback mechanism that reinforces global warming.

> One of the strongest signals of climate change should be a loss of sea ice in the Arctic.

The effects of climate change aren't observed only in the Arctic. In July 2017, an iceberg the size of Delaware broke off of Antarctica's Larsen C ice shelf and began to drift across the choppy waters of the Weddell Sea.

(Ice shelves are different from sea ice—ice shelves are much thicker, form on land, and move as glacial ice off a continent, mainly Antarctica.)

Although this is a natural process, scientists fear that global warming will accelerate the rate at which this and other ice shelves, including those around Canada's Ellesmere Island, will break up. Because ice shelves are already floating in the ocean, they do not contribute directly to sea-level rise when they break up. However, glaciers constantly push against ice shelves. Because these ice shelves are often anchored by rock peninsulas and islands, they slow the rate of glacial advance. The removal of ice shelves would allow glaciers over the continent to flow freely into the ocean, which would cause a significant rise in sea level.

Permafrost

During the past decade, mounting evidence has indicated that the extent of *permafrost* in the Northern Hemisphere has decreased, as would be expected under long-term warming conditions. In the Arctic, short summers thaw only the top layer of frozen ground. The permafrost beneath this *active layer* is like the cement bottom of a swimming pool. In summer, water cannot percolate downward, so it saturates the soil above the permafrost and collects on the surface in thousands of lakes. However, as Arctic temperatures climb, the bottom of the “pool” seems to be “cracking.” Satellite imagery shows that significant numbers of lakes have shrunk or disappeared altogether.

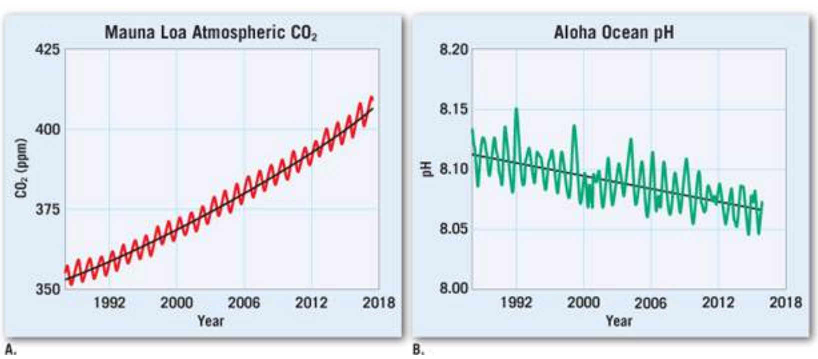
Thawing permafrost represents a potentially significant positive-feedback mechanism that will reinforce global warming. When vegetation dies in the Arctic, cold temperatures inhibit its decomposition. Consequently, over thousands of years, a great deal of organic matter has become stored in the permafrost. When the permafrost thaws, organic matter that may have been frozen for millennia comes out of “cold storage” and decomposes. The result is the release of carbon dioxide and methane—greenhouse gases that contribute to global warming. Thus, like decreasing sea ice, thawing permafrost is a positive-feedback mechanism.

Increasing Ocean Acidity

The human-induced increase in the amount of carbon dioxide in the atmosphere has some serious implications for ocean chemistry and marine life. Nearly half of the human-generated carbon dioxide ends up dissolved in the oceans. When carbon dioxide (CO_2) from the atmosphere dissolves in seawater (H_2O), it forms carbonic acid (H_2CO_3), which lowers the ocean's pH and changes the balance of certain chemicals found naturally in seawater. (See Figure 13.18, to review the pH scale.) In fact, the oceans have already absorbed enough CO_2 for surface waters to have experienced a pH decrease of 0.1 since preindustrial times—which means that seawater is more acidic (Figure 14.26). Moreover, if the current trend in CO_2 emissions continues, by the year 2100 the ocean will have experienced a pH decrease of at least 0.3, which represents a change in ocean chemistry that has not occurred for millions of years.

Figure 14.26 Oceans becoming more acidic

The graphs show the correlation between rising levels of CO_2 in the atmosphere as measured at Mauna Loa Observatory (**A**) and falling pH in the nearby ocean (**B**). As CO_2 accumulates in the ocean, the water becomes more acidic (pH declines).



> The human-induced increase in the amount of carbon dioxide in the atmosphere is likely to increase the acidity of the oceans, which can be detrimental to marine life.

This shift toward acidity and the resulting changes in ocean chemistry make it more difficult for certain marine organisms to build hard parts (shells) out of calcium carbonate. The decline in pH thus threatens a variety of calcite-secreting organisms as diverse as microbes and corals. This concerns marine scientists because of the potential consequences for other sea life that depend on the health and availability of these organisms.

The Potential for “Surprises”

You have seen that Earth′s climate in the twenty-first century, unlike during the preceding thousand years, is not expected to be stable. The amount and rate of future climate shifts depends primarily on current and future human-caused emissions of heat-trapping gases and airborne particles. Many of the changes will probably be gradual environmental shifts, imperceptible from year to year. Nevertheless, the effects, accumulated over decades, will have powerful economic, social, and political consequences.

Despite our best efforts to understand future climate shifts, there is also the potential for ″surprises.″ This simply means that the complexity of Earth′s climate system might lead to relatively sudden, unanticipated changes or unexpected shifts in some aspects of climate. Many projections predict steadily changing climate conditions, giving the impression that humanity will have time to adapt. However, the scientific community has been paying attention to the possibility that at least some changes will be abrupt, perhaps crossing a threshold, or ″tipping point,″ so quickly that there will be little time to react.

This is a reasonable concern because abrupt changes occurring over periods as short as decades or even years have been a natural part of the climate system throughout Earth history. One such abrupt change occurred at the end of a time span known as the *Younger Dryas*, a time of abnormal cold and drought in the Northern Hemisphere that occurred about 12,000 years ago. Following this 1000-year-long cold period, the Younger Dryas abruptly ended in a few decades or less and is thought to have contributed to the extinction of more than 70 percent of large-bodied mammals in North America.

The impact on climate of an increase in atmospheric CO_2 and trace gases is obscured by some uncertainties. Yet climate scientists continue to improve our understanding of the climate system and the potential impacts of global climate change. Policymakers must respond to the risks posed by greenhouse gas emissions, knowing that our understanding is imperfect. However, they are also faced with the fact that climate-induced environmental changes cannot be reversed quickly, if at all, and that any response will require cooperation among countries and international organizations to be effective.

Concept Checks 14.6

- Describe the factors that are causing sea level to rise.
- How is Arctic sea ice changing, and what impact might this have on future climate change? Does this change represent positive- or negative-feedback mechanisms?
- Based on Figure 14.21, what projected changes relate to something other than temperature?

Concepts in Review

14.1 Climate Change

LO 1 Explain how unraveling past climate change is related to the climate system.

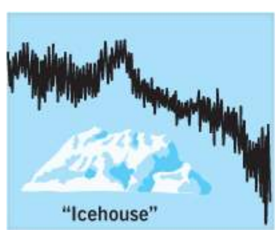
Key Terms

climate system

cryosphere

Quaternary Ice Age

- Earth's climate system is a complex interchange of energy and moisture that occurs among the atmosphere, hydrosphere, geosphere, biosphere, and cryosphere (ice and snow).
- There have been many shifts in Earth's climate in the distance past, from warm to cold and back again, which have impacted life on Earth.



14.2 Detecting Climate Change

LO 2 Describe several ways to detect evidence of climate change.

Key Terms

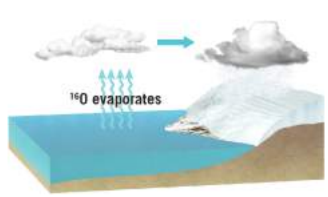
proxy data

paleoclimatology

oxygen-isotope analysis

dendrochronology

- The geologic record yields multiple kinds of indirect evidence about past climate. These proxy data can be found in glacial ice cores, seafloor sediment, oxygen isotopes, corals, tree rings, and fossil pollen.
- Oxygen-isotope analysis is based on the difference between heavier ^{18}O and lighter ^{16}O and their relative amounts in water molecules (H_2O). This ratio can be used to gauge how warm or cold temperatures are. Oxygen isotopes can also be measured in the shells of fossil marine organisms, in coral structures, or in the water molecules that make up glacial ice.
- Trees grow thicker rings in warmer, wetter years and thinner rings in colder, drier years. The pattern of ring thickness can be matched up between trees of overlapping ages for a long-term record of a region's climate.



14.3 Natural Causes of Climate Change

LO 3 Discuss four natural phenomena that cause climate change.

Key Terms

plate tectonics theory

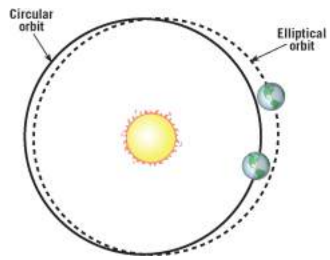
eccentricity

obliquity

precession

sunspots

- The natural functions of the Earth system produce climate change. The position of lithospheric plates can influence the climate of the continents as well as oceanic circulation, which in turn affect climate.
- Variations in the shape of Earth's orbit, angle of axial tilt, and orientation of the axis all cause changes in the distribution of solar energy at Earth's surface.
- Since Earth's climate is fueled by solar energy, variations in the Sun's energy output matter. Sunspots are dark features on the Sun's surface associated with periods of slightly increased solar energy output.
- Volcanic aerosols act like a Sun shade, screening out a portion of incoming solar radiation for as long as several years.



14.4 Human Impacts on Global Climate

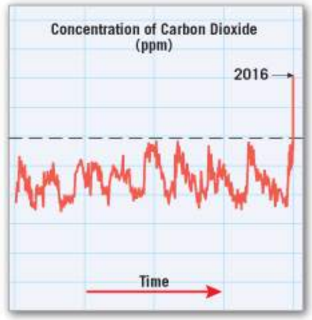
LO 4 Summarize the nature and cause of the atmosphere's changing composition since about 1750. Describe the climate's response.

Key Terms

trace gases

black carbon

- By altering ground cover with the use of fire and the overgrazing of land, people have modified climatic factors such as surface albedo and evaporation rates for thousands of years.
- Human activities produce climate change through the release of carbon dioxide (CO_2) and trace gases, such as methane and nitrous oxide. Humans release CO_2 when they cut down forests or when they burn fossil fuels such as coal, oil, and natural gas.
- A steady rise in atmospheric CO_2 levels has been documented at Mauna Loa, Hawaii, and other locations around the world.
- Air bubbles trapped in glacial ice reveal that there is currently about 40 percent more CO_2 than the atmosphere has contained in the past 650,000 years.
- As a result of greenhouse gases, Earth's atmosphere has warmed by about 0.8°C (1.4°F) in the past 100 years, most of it since the 1970s. Temperatures are projected to increase by another 2° to 4.5°C (3.5° to 8.1°F) in the future.
- Overall, aerosols reflect a portion of incoming solar radiation back to space and therefore have a cooling effect.


Concentration of Carbon Dioxide
(ppm)
2016
Time

14.5 Predicting Future Climate Change

LO 5 Contrast positive- and negative-feedback mechanisms and provide examples of each.

Key Terms

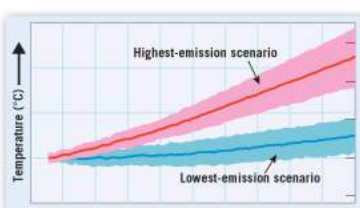
feedback mechanism

positive-feedback mechanism

negative-feedback mechanism

general circulation models (GCMs)

- A change in one part of the climate system may trigger changes in other parts of the climate system that amplify or diminish the initial effect. These climate-feedback mechanisms are called positive-feedback mechanisms if they reinforce the initial change and negative-feedback mechanisms if they counteract the initial effect.
- The melting of sea ice due to global warming (decreasing albedo and increasing the initial effect of warming) is one example of a positive-feedback mechanism.
- Computer models of climate give scientists a tool for testing hypotheses about climate change. Although these models are simpler than the real climate system, they are useful tools for predicting Earth's future climate.



14.6 Some Consequences of Climate Change

LO 6 Suggest several likely consequences of global climate change.

- In the future, temperature increases will likely be greatest in the polar regions and least in the tropics. Some areas will get drier, whereas other areas will get wetter.
- Sea level is predicted to rise because of melting of glacial ice and thermal expansion of seawater. Low-lying, gently sloped, highly populated coastal areas are most at risk.
- Sea ice cover and thickness in the Arctic have been declining since satellite observations began in 1979.
- Because of the warming of the Arctic, permafrost is melting, releasing CO_2 and methane to the atmosphere, which is a positive-feedback mechanism.
- Because the climate system is imperfectly understood, it could produce sudden, unexpected changes with little warning.

Arctic sea ice

Exercises and Online Activities

Mastering Meteorology™

For instructor-assigned homework, test prep resources, and other learning materials, visit **Mastering Meteorology.**

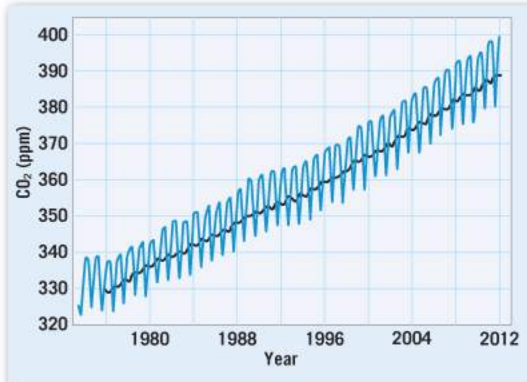
Review Questions

1. Why is it important to monitor all parts of the climate system?
2. Briefly describe the Quaternary Ice Age.
3. Define *proxy data*.
4. What is meant by paleoclimatology?
5. What do ice cores tell us about the composition of the atmosphere in the distant past?
6. Explain how dendrochronology is used to study past climate conditions.
7. Explain the theory of plate tectonics and how it explains past climate conditions.
8. Define *eccentricity*, *obliquity*, and *precession*, and describe how they may explain climate change.
9. Is there a strong link between volcanic eruptions and long-term climate change? Why or why not?
10. How does population growth impact climate change?
11. Connect changes in the levels of trace gases in the atmosphere to changes in temperature.
12. Are aerosols natural, human-made, or both? What is black carbon?
13. Define *feedback mechanism*, and provide two examples.
14. Why are computer models necessary to understand climate change? Why are they not perfect?
15. Give an example of a cloud type that tends to cool the surface of the Earth.
16. What are the consequences of shrinking glaciers?
17. List three effects of sea-level rise on human settlements.
18. How might melting permafrost accelerate climate change?
19. What is the connection between climate change and changes in marine life?

Give It Some Thought

1. The accompanying photo is of the Athabasca Glacier in the Canadian Rockies. The marker indicates the location of the outer limit of this glacier in 1925. Is the behavior of Athabasca Glacier shown in this image typical of other glaciers around the world? Describe a significant impact of such behavior.

2. Describe one way in which the biosphere records changes in the climate system. Provide an example of how the biosphere is affected by climate change, and an example of how a change in the biosphere can cause climate change.
3. It has been suggested that global warming over the past 40 years might have been even greater were it not for the effect of certain types of air pollution. Explain how this could be true.
4. The accompanying graph shows changes in the air's CO_2 content at South Pole Station (90° south latitude) and at a similar facility at Barrow, Alaska (71° north latitude). Which line on the graph represents the South Pole, and which represents Barrow, Alaska? Explain how you were able to determine which line is which.



5. During a conversation, an acquaintance indicates that he is skeptical about global warming. When you ask him why he feels that way, he says, "The past couple of winters in this area have been among the coolest I can remember." While you assure this person that it is useful to question scientific findings, you suggest that his reasoning in this case may be flawed. Use your understanding of the definition of *climate* along with one or more graphs in the chapter to persuade this person to reevaluate his reasoning.
6. Explain how oxygen-isotope analysis of the fossil shells of marine animals can tell us how much water is trapped in glacial ice and, hence, the status of global climate at the time those animals lived.

Beyond the Textbook

Climate Change in High Latitudes

The effects of a warming atmosphere are most pronounced in the high latitudes of the Northern Hemisphere. For more than 30 years, the extent and thickness of Arctic sea ice, mountain glaciers, and continental ice sheets have been rapidly declining.

1. Columbia Glacier*

Columbia Glacier flows directly into the sea and is one of the most rapidly changing glaciers in the world. Go to the Earth Observatory page at http://earthobservatory.nasa.gov/. Click on World of Change in the Special Collections column located in the lower right, and select Columbia Glacier, Alaska, by clicking on the image. Watch the animation, and then read the description below the image.

1. This is a false-color satellite image of Columbia Glacier and its tributaries. What does the color cyan represent on the map? Green? Brown? Dark blue?
2. What term is used to describe the nose or farthest extent of a glacier? (Note that the light bluish area just south of the nose of the glacier is a layer of floating ice containing icebergs that have calved from the glacier.)
3. In what year did the Columbia Glacier become unstable and begin to retreat?
4. What role does the underwater ridge produced by the terminal moraine play in ice accumulation downstream of the terminus?
5. How far has the Columbia Glacier retreated in the last three decades?
6. How does the retreat of glaciers affect sea level?

2. Arctic Sea Ice

Climate models are in general agreement that one of the strongest signals of climate change should be a loss of sea ice in the Arctic. Go back to World of Change link, and select Arctic Sea Ice by clicking on the image. Watch the animation, and read the information below the images.

1. In what month does Arctic sea ice reach its maximum extent and concentration?
2. In what month does the sea ice reach its minimum extent and concentration?
3. Explain what the orange lines on these images illustrate.
4. How is the area with the highest ice concentration shown on these images? How is open water shown?
5. In which year did the Arctic sea ice seem to have the least extent and concentration?
6. Compare and contrast the September 1999 image with the September 2016 image.
7. Compare and contrast the March 2000 image with the March 2017 image located on the right.
8. Arctic sea ice floats on the Arctic Ocean, so when it melts it does not cause a rise in sea level. With that in mind, explain the role that Arctic sea ice plays in climate change.

* This activity was modified from *Geosystems* by Robert W. Christopherson.

Chapter 15 World Climates

Autumn morning in Tuscany, Italy, a region that exhibits a mediterranean climate.

Focus on Concepts

Each statement represents the primary learning objective for the corresponding major heading within the chapter. After you complete the chapter, you should be able to:

1. Describe the criteria used in the Köppen system of climate classification. List and briefly discuss the major controls of climate (15.1).
2. Distinguish among the three categories of humid tropical climates (15.2).
3. Contrast low-latitude dry climates and middle-latitude dry climates (15.3).
4. Distinguish among the three categories of C climates (15.4).
5. Summarize the characteristics of the two categories of D climates (15.5).
6. Contrast tundra and ice cap climates (15.6).
7. List the characteristics of highland climates (15.7).

The varied nature of Earth's surface (oceans, mountains, plains, ice sheets) and the many interactions that occur among atmospheric processes give every location on our planet a distinctive and often unique climate. Therefore, we cannot describe the climatic character of countless locales; that would require many volumes. Our purpose is to introduce you to the *major climate regions* of the world. We will examine large areas and zoom in on particular places to illustrate the characteristics of these major climate regions.

15.1 Climate Classification and Controls

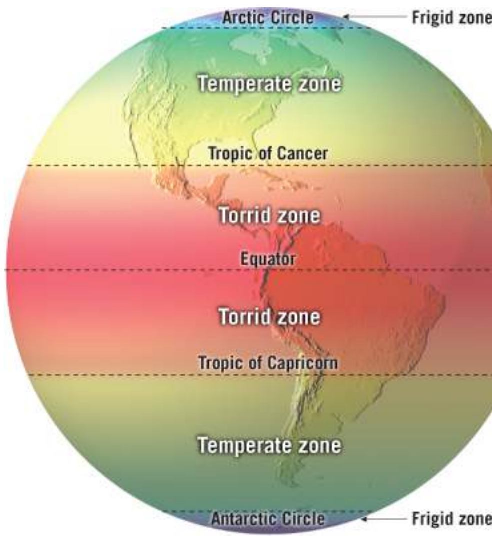
LO 1 Describe the criteria used in the Köppen system of climate classification. List and briefly discuss the major controls of climate.

Temperature and precipitation are the most important elements in climate descriptions because these factors have the greatest influence on people and the environment. The worldwide distribution of temperature and precipitation can vary considerably on a daily basis—making it unlikely that any two places experience identical weather, even if they are geographically close together. To bring order to such a variety of weather patterns, scientists have devised various methods to *classify climate*.

One early attempt at climate classification was made by the ancient Greeks, who divided each hemisphere into three zones: *torrid*, *temperate*, and *frigid* (Figure 15.1). The basis of this simple scheme was Earth–Sun relationships. The boundaries were the four astronomically important parallels of latitude: the Tropic of Cancer (23.5° north), the Tropic of Capricorn (23.5° south), the Arctic Circle (66.5° north), and the Antarctic Circle (66.5° south). Thus, the globe was divided into winterless climates, summerless climates, and an intermediate type that had features of the other two.

Figure 15.1 **An early climate classification**

The ancient Greeks divided each hemisphere into three zones. The winterless *torrid zone* was separated from the summerless *frigid zone* by the *temperate zone*, which had features of the other two.



An early attempt at climate classification by the Greeks divided each hemisphere into three zones: torrid, temperate, and frigid.

The Köppen Classification System

By the beginning of the twentieth century, many climate classification systems had been devised. One of the most widely used was developed by German climatologist Wladimir Köppen. The **Köppen classification system** is based on easily obtained data: mean monthly and annual temperature and precipitation. Furthermore, the criteria Köppen used for dividing the world in climate groups are relatively easy to obtain and apply.

Since it was first introduced, the Köppen classification system has been revised several times. As a result, the classification system used in this book is more appropriately called the *modified Köppen classification system*. It retains the basic characteristics of the Köppen system but includes some modifications, mainly in regard to midlatitude climates.

> The Köppen classification system is based on easily obtained data: mean monthly and annual temperature and precipitation.

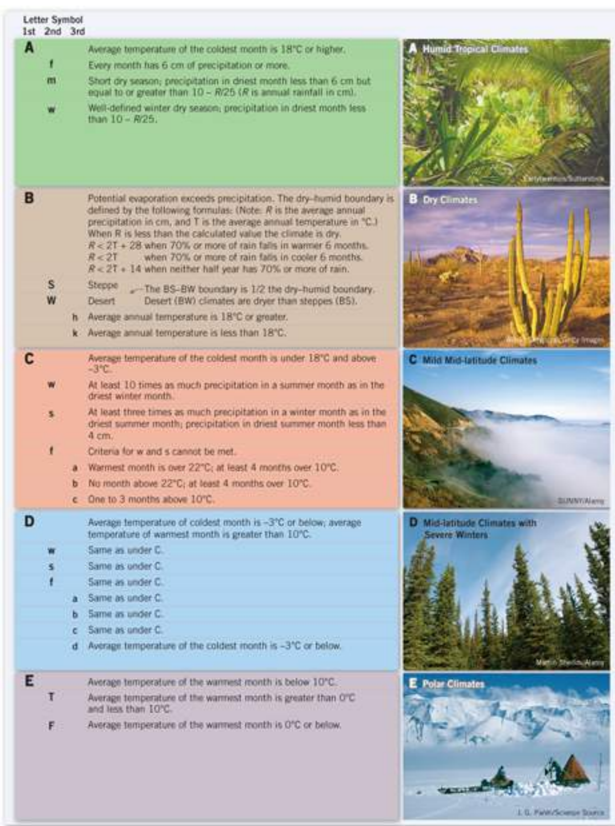
Köppen believed the distribution of natural vegetation was the best expression of overall climate because all plants have certain temperature and moisture requirements. Thus he classified climate groups largely by the presence of certain groups of plants. He recognized five principal climate groups, each designated by a capital letter:

A	***Humid tropical climates.*** Winterless climates, with all months having a mean temperature above 18°C (64°F).
B	***Dry climates.*** Climates where evaporation exceeds precipitation, resulting in a moisture deficiency.
C	***Mild midlatitude climates.*** Climates where average temperature of the coldest month is below 18°C (64°F) but above –3°C (27°F).
D	***Midlatitude climates with severe winters.*** Climates where the average temperature of the coldest month is below –3°C (27°F) and the warmest monthly mean exceeds 10°C (50°F).
E	***Polar climates.*** Summerless climates, where the average temperature of the warmest month is below 10°C (50°F).

Notice that four of these major groups (A, C, D, and E) are defined on the basis of *temperature*, whereas the B group has *precipitation* as its primary criterion. Each of the five groups is further subdivided by using the criteria and letters presented in Figure 15.2. In this chapter, we will also consider another climate group not in the original Köppen system, called *highland climates (H)*.

Figure 15.2 **The Köppen system of climate classification**

Letters are used to denote the different climate types. When using this figure to classify climate data, first determine whether the data meet the criteria for E climates. If the station is not a polar climate, proceed to the criteria for B climates. If the data do not fit into either the E or B groups, check the data against the criteria for A, C, and D climates, in that order.

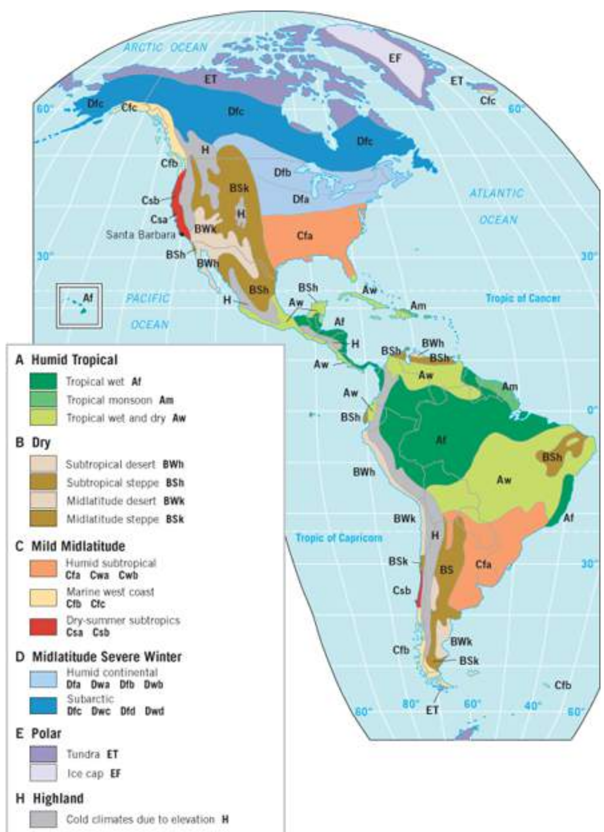


A strength of the Köppen system is that the boundaries between climate groups are relatively easy to determine. However, these boundaries are not fixed—rather, they shift positions from one year to the next. Climate boundaries on maps are simply average locations based on data collected over many years and should be regarded as broad transition zones and not distinct lines.

The world distribution of climates, according to the Köppen classification, is shown in Figure 15.3. We will refer you to this map several times as we examine Earth's climates in the following sections. After reviewing the controls of climate, we devote the remainder of this chapter to a tour of world climates.

Figure 15.3 **Climates of the world**

This map is based on the Köppen classification.



Climate Controls: A Summary

If Earth's surface were completely homogeneous, the map of world climates would be simple—consisting of a series of latitudinal bands girdling the globe on each side of the equator (see Figure 15.1). This is not the case, of course. Earth is not a homogeneous sphere, and many factors disrupt the symmetry just described.

At first glance, the world climate map (see Figure 15.3) reveals what appears to be a haphazard pattern, with similar climates located in widely separated parts of the world. A closer examination shows that although they may be far apart, locations experiencing similar climates are generally found at similar latitudes and roughly the same positions relative to the continents. For example, Santa Barbara, California, and Lisbon, Portugal, are both located along the west coasts of their respective continents and are within about 4° latitude of each other (Figure 15.3). Both cities experience dry-summer subtropical climates (Csa, Csb), also called mediterranean climates. This consistency suggests an order in the distribution of climates and that the pattern of climates is not by chance. Indeed, the climate pattern shown in Figure 15.3 reflects the major climate controls: latitude, land and water, geographic position and prevailing winds, mountains and highlands, ocean currents, and pressure and wind systems.

> Locations experiencing similar climates are generally found at about the same latitude and at roughly the same positions relative to the continents.

Latitude

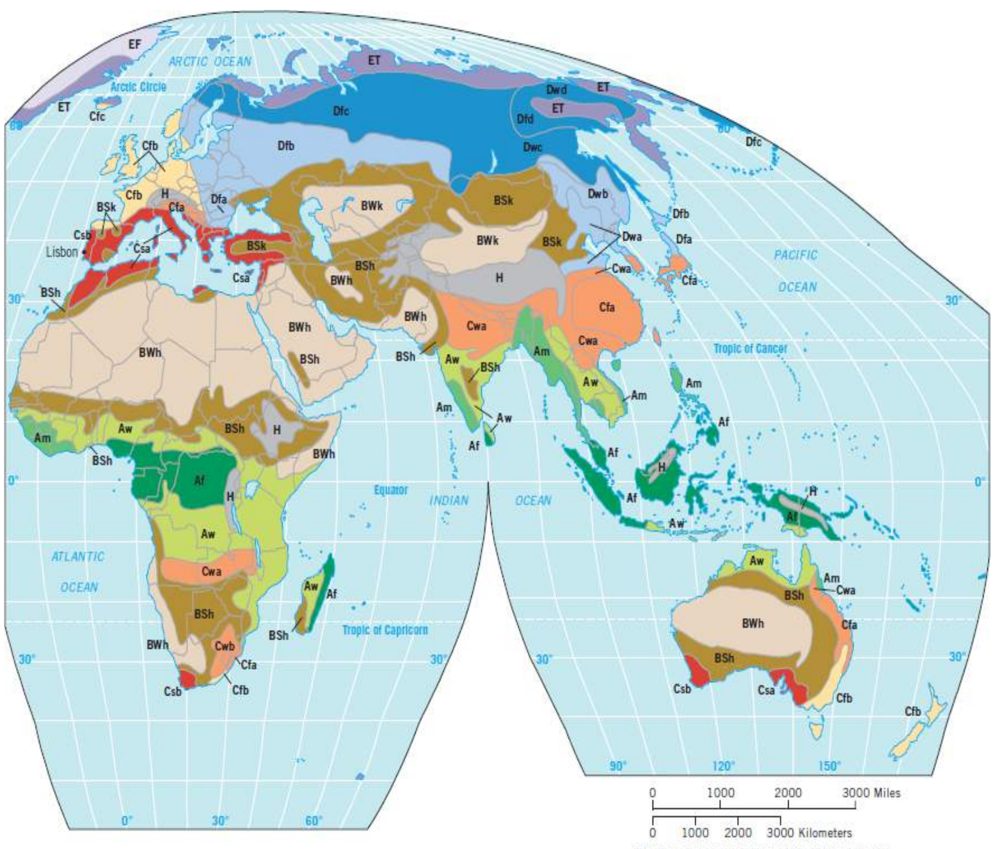
Variations in the amount of solar radiation received at Earth's surface are the single greatest cause of temperature differences. Although variations in such factors as cloud coverage and the amount of dust in the air may be locally influential, seasonal changes in Sun angle and length of daylight are the most important factors controlling global temperature distribution.

Recall that all places located at the same latitude have identical Sun angles and hours of daylight and, hence receive roughly the same amount of solar energy. As a result, places located at the same latitude generally experience similar temperature regimes. Moreover, because the vertical rays of the Sun migrate annually between the Tropic of Cancer and the Tropic of Capricorn, there is a regular latitudinal shifting of temperatures. Temperatures in the tropical realm are consistently high because the vertical rays of the Sun are never far away. As one moves farther poleward, however, greater seasonal fluctuations in the receipt of solar energy result in larger annual temperature ranges.

Land and Water

The distribution of land and water must be considered second only to latitude in importance as a control of temperature. Recall from Chapter 3 that water has a greater *heat capacity* than rock and soil. Thus, land heats more rapidly and to higher temperatures than water, and it cools more rapidly and to lower temperatures than water. Consequently, variations in air temperatures are much greater over land than over water. This differential heating of Earth’s surface has led to the division of climates into two broad classes—*marine* and *continental*.

> Land and water differences strongly control climate—marine climates are relatively mild, whereas continental climates are typically more extreme.



Watch **Video: The Ocean's Green Machines**

Marine climates are considered relatively mild for their latitude because the moderating effect of water produces summers that are warm but not hot and winters that are cool but not cold. In contrast, **continental climates** tend to be much more extreme. Although a marine station and a continental station along the same parallel in the middle latitudes may have similar annual mean temperatures, the annual temperature *range* will be far greater at the continental station.

Geographic Position and Prevailing Winds

To understand the influence of land and water on the climate of an area, we must consider the position of that area on the continent and its relationship to that area's prevailing winds. The moderating influence of water is much more pronounced along the windward side of a continent, for here the prevailing winds may carry the maritime air masses far inland. In contrast, places on the lee side of a continent, where the prevailing winds blow from the land toward the ocean, are likely to have a more continental temperature regime.

Mountains and Highlands

Mountains and highlands play an important part in the distribution of climates, which can be illustrated by examining the western United States. Because prevailing winds are from the west, the mountain chains that trend north–south form major barriers—preventing the moderating influence of maritime air masses from reaching far inland. Consequently, a location on the east side of Sierras that lies within a few hundred kilometers of the Pacific Ocean has a temperature regime that is essentially continental—as such, it experiences warmer summers and colder winters compared to locations at the same latitude along the Pacific coast.

In addition, these topographic barriers trigger orographic rainfall on their windward slopes, often leaving a dry rain shadow on the leeward side (see Box 4.4). Similar effects may be seen in South America and Asia, where the towering Andes and the massive Himalayan system are major barriers.

Extensive highlands create their own climatic regions. Because temperatures decrease with increasing altitude, areas such as the Tibetan Plateau, the Altiplano of Bolivia, and the uplands of East Africa are much cooler than their latitudinal locations alone would indicate.

> Mountains and highlands prevent maritime air masses from reaching far inland and trigger orographic precipitation on their windward slopes.

Ocean Currents

The effect of ocean currents on the temperatures of adjacent land areas can be significant. Recall from Chapter 7 that poleward-moving currents, such as the Gulf Stream, cause air temperatures to be warmer than would be expected for their latitudes. This influence is especially pronounced in winter.

Conversely, the cold California Current causes the temperatures of coastal regions that border this current to be significantly cooler in the summer than nearby locations that are farther inland. This can be confirmed by comparing summer temperatures in Sacramento, California, to those of nearby San Francisco (see Table 15.7). In addition, the chilling effects of these cold currents act to stabilize the air masses moving across them. The result is marked aridity and often considerable advection fog.

> Poleward-moving warm ocean currents cause air temperatures to be warmer than would be expected, whereas equatorward-moving cold currents promote cooler-than-expected temperatures.

Pressure and Wind Systems

The global distribution of precipitation shows a close relationship to the distribution of Earth's major pressure and wind systems. In the realm of the equatorial low, the convergence of warm, moist, and unstable air makes this a zone of heavy rainfall. In regions dominated by subtropical highs and subsidence, general aridity prevails, creating major deserts. Farther poleward in the middle latitudes, the influence of the many traveling cyclonic disturbances increases precipitation. Finally, in polar regions, where temperatures are low and the air can hold only small quantities of moisture, precipitation totals decline.

The seasonal shifting of the pressure and wind belts, which follows the movement of the Sun's vertical rays, significantly affects areas between these belts. Such regions are alternately influenced by two different pressure and wind systems. For example, a locale poleward of the equatorial low yet equatorward of the subtropical high will experience a summer rainy period as the low pressure migrates poleward. By contrast, the same locale experiences a wintertime dry season as the high moves equatorward. This latitudinal shifting of pressure belts is largely responsible for the seasonality of precipitation in many regions.

Concept Checks 15.1

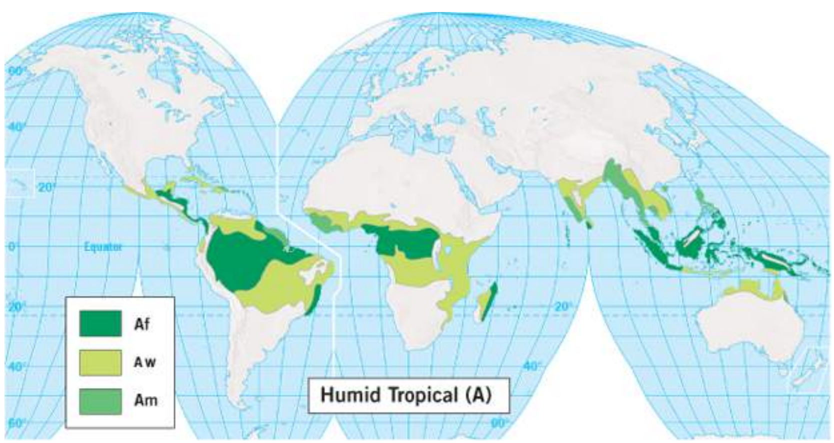
- What climate data are used in the Köppen classification scheme?
- List the major climate controls, and briefly describe their influence.
- Which of the controls you identified in Question 2 has the greatest influence on global temperature?

15.2 Humid Tropical Climates (A)

LO 2 Distinguish among the three categories of humid tropical climates.

The *humid tropical climates (A)* are winterless climates characterized by warm temperatures and the prevalence of moisture. Although rain is not necessarily a daily occurrence, many of the globe's wettest places belong to this climate group. Within the humid tropical climates three types are recognized: tropical wet climate (Af), tropical wet and dry climate (Aw), and tropical monsoon climate (Am) (Figure 15.4). Each climate type has an associated vegetation type.

Figure 15.4 The global distribution of humid tropical (A) climates



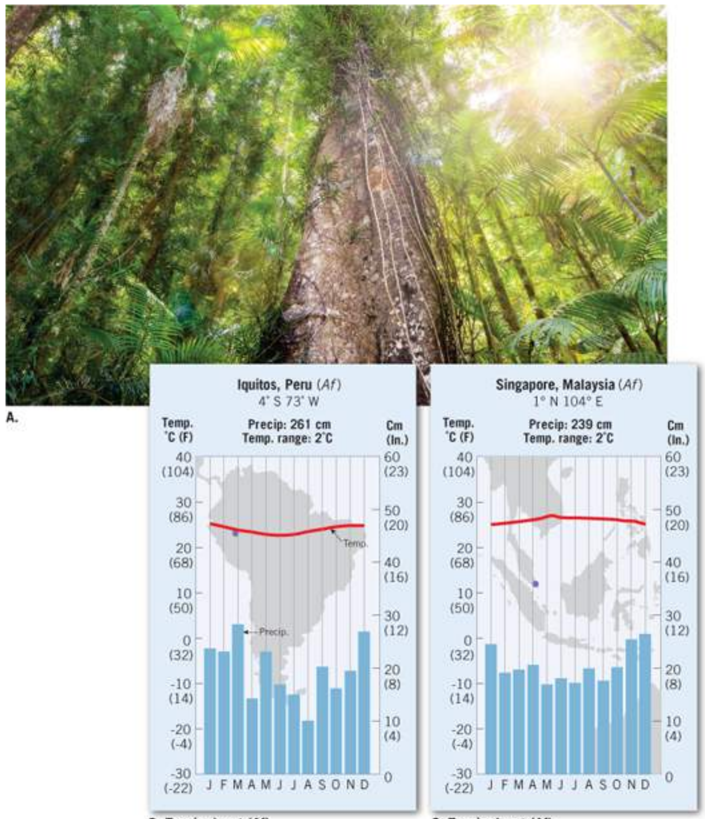
Tropical Wet Climate (Af)

The **tropical wet climate (Af)**, noted for its year-round high temperatures and abundant rainfall, is often simply referred to as the *wet tropics*. The consistently high temperatures and abundant rainfall, coupled with meager winds, account for the region's reputation as "oppressive" and "monotonous."

These weather conditions combine to produce the most luxuriant vegetation in any climatic realm: the **tropical rain forest** (Figure 15.5A). Unlike the forests you may be accustomed to, tropical rain forests consist of broadleaf trees that remain green throughout the year. In addition, instead of being dominated by a few species, it is common for hundreds of different species to inhabit a single square kilometer of the rain forest (Box 15.1).

Smartfigure 15.5 **The wet tropics (Af)**

A. The tropical rain forest is characterized by hundreds of different species per square kilometer. **B.** Climographs show average monthly temperatures and precipitation totals for a given location. Iquitos, an Af station, is wet throughout the year. **C.** Climograph for Singapore.



A.

B. Tropical wet (Af)

C. Tropical wet (Af)

Watch **SmartFigure: Tropical Climates**

Box 15.1

Clearing the Tropical Rain Forest

Over the past few decades, the destruction of tropical forests has become an important environmental issue. Each year millions of acres are cleared for agriculture and logging (Figure 15.A). This clearing has contributed to soil degradation, the loss of biodiversity, and climate change.

Figure 15.A Tropical deforestation

Clearing the tropical rain forest in Surinam. The thick reddish soils are highly leached and therefore nutrient poor.

Thick red soils are common in the wet tropics and subtropics. They are the end product of extreme chemical weathering. Because lush tropical rain forests are associated with thick soils, many people assume that they are fertile and have great potential for agriculture. Yet just the opposite is true: They are among the poorest soils for farming. How can this be?

Because rain forest soils develop under conditions of high temperature and heavy rainfall, they are severely leached—that is, the movement of large quantities of water through the soil removes soluble materials. The result is that insoluble oxides of iron and aluminum become concentrated in the soil. Iron oxides give the soil its distinctive red color, but it has little nutritional value. Also, because bacterial activity is very high in the tropics, rain forest soils contain practically no organic material. Therefore, even though the vegetation is dense and luxuriant, the soil itself contains few available nutrients.

Most nutrients that support the rain forest are locked up in the trees themselves. As vegetation dies and decomposes, the roots of the trees quickly absorb the nutrients before they are leached from the soil. These nutrients are continuously recycled as trees die and decompose. Therefore, clearing forests for farming or to harvest the timber removes most of the nutrients as well.

Clearing rain forests also accelerates erosion. Tree roots anchor the soil, and leaves and branches provide a canopy that protects the ground by deflecting the full force of the frequent heavy rains. When the protective vegetation is gone, soil erosion increases.

Apply What You Know

1. Why are tropical rain forest soils red in color?
2. Where are most plant nutrients found in a tropical rain forest?

Standing on the shaded floor of a tropical rain forest looking upward, one sees tall, smooth-barked, vine-entangled trees, the trunks branchless in their lower two-thirds, with an almost continuous canopy of foliage above. The very top of the forest may be seen through an occasional opening, where the crowns of the trees tower 40 meters (130 feet) or more above the forest floor.

Figure 15.4 shows that Af climates form a discontinuous belt astride the equator that typically extends 5° to 15° into each hemisphere. The poleward margins are most often marked by diminishing rainfall, but occasionally decreasing temperatures mark the boundary. Because of the general decrease in temperature with height in the troposphere, this climate region is restricted to elevations below 1000 meters (3300 feet). Consequently, the major interruptions near the equator are mostly cooler highland areas.

> The tropical wet climate (Af) exhibits constant high temperatures and year-round rainfall that combine to produce the most luxuriant vegetation of any climatic realm—the tropical rain forest.

Data for representative stations in the tropical wet climate zone is shown in the form of *climographs* in Figure 15.5B and 15.5C, which reveal the most obvious features characterizing the climate in these areas—high average temperatures and year-round rainfall.

Temperature

Because places with an Af designation lie near the equator, the Sun's rays are nearly vertical, and changes in day length are minimal throughout the year. Thus, temperatures average 27°C (80°F) or higher each month, as shown in Figure 15.5B and 15.5C. Cloud cover, rather than the position of the Sun, most often accounts for the small difference that exists between the warmest and coolest months.

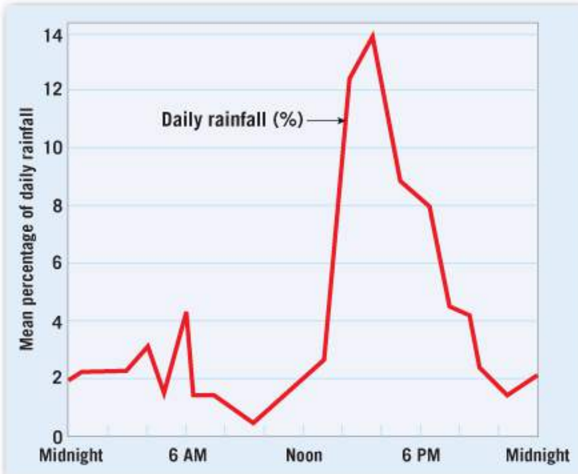
Precipitation

Areas dominated by Af climate usually receive more than 200 centimeters (80 inches) of rain each year (Figure 15.5B, 15.5C). The rainy nature of the equatorial realm is partly related to extensive heating and the region's proximity to the equatorial low, which triggers thermal convection. In addition, this is the zone of the converging trade winds, called the **intertropical convergence zone (ITCZ)**. Convergence along the ITCZ, coupled with thermal convection, leads to widespread ascent of the warm, humid, unstable air. Conditions near the equator are thus ideal for generating precipitation.

Rain typically falls on more than half of the days each year. In fact, at some stations, rainfall occurs nearly 75 percent of the days. There is also a marked daily regularity to the rainfall at most places. Cumulus clouds begin forming in late morning or early afternoon. The buildup continues until about 3:00 or 4:00 p.m., the time when temperatures are highest and thermal convection is at a maximum; then the cumulonimbus towers yield showers. Figure 15.6, showing the hourly distribution of rainfall at Kuala Lumpur, Malaysia, exemplifies this pattern. However, the daily rain cycle is different at many marine stations, with the rainfall maximum occurring at night instead of in the afternoon. This difference can often be attributed to radiation cooling from cloud tops at night, which increases the environmental lapse rate and hence enhances instability.

Figure 15.6 The distribution of rainfall by time of day at Kuala Lumpur, Malaysia

With its midafternoon maximum, Kuala Lumpur illustrates the typical pattern at many wet tropical stations.



> Although rainfall may not be evenly distributed throughout the year, tropical rain forest stations are wet in all months.

You might have wondered . . .

Isn't *jungle* just another word for *tropical rain forest*?

Although both terms refer to vegetation in the wet tropics, they are not the same. The tropical rain forest's high canopy of foliage does not allow much light to penetrate to the ground. As a result, plant foliage is relatively sparse on the dimly lit forest floor. By contrast, anywhere considerable light makes its way to the ground, as along riverbanks or in human-made clearings, an almost impenetrable growth of tangled vines, shrubs, and short trees exists. The familiar term *jungle* is used to describe such areas.

Tropical Wet and Dry (Aw)

Between the rainy tropics and the subtropical arid regions lies a transitional climatic region called the **tropical wet and dry climate (Aw)**. Along its equatorward margin, the dry season is short. By contrast, along the poleward side, the dry season is prolonged, and conditions merge into those of the adjacent semiarid regions.

In the tropical wet and dry climate, the rain forest gives way to the **savanna**, a tropical grassland with scattered brush and deciduous trees. The rainy season is usually too short on a savanna to support forests. The most widely known savanna is the Serengeti Plain of East Africa with its distinctive acacia trees—a region known for its lions, zebras, elephants, and giraffes (Figure 15.7). Savannas are also found in areas surrounding the rainforests in South America as well as in parts of India and northern Australia (see Figure 15.4). In Australia, eucalyptus trees take the place of acacia trees. Because the tropical wet and dry (Aw) climate supports this distinctive tall grassland, it is often called a *savanna climate*.

Figure 15.7 Tropical savanna grassland

Tropical savanna in Tanzania's Serengeti National Park, with lions in the foreground and its stunted, drought-resistant trees in the background.

> The tropical wet and dry (Aw) climate region is a transitional zone between the rainy tropics and the arid subtropics, where the rain forest gives way to the savanna—a tropical grassland with scattered deciduous trees.

Temperature

Data on temperatures show only modest differences between the wet tropics and the tropical wet and dry regions, as shown in Table 15.1. Because of the somewhat higher latitude of most Aw stations, annual mean temperatures are slightly lower. In addition, the annual temperature range is a bit higher, varying from 3°C (5°F) to perhaps 10°C (20°F).

Table 15.1 Data for Tropical Wet and Dry Stations (Aw)

	J	F	M	A	M	J	J	A	S	O	N	D	YR
Calcutta, India, 22° 32 N; 6 m													
Temp. (°C)	20.2	23.0	27.9	30.1	31.1	30.4	29.1	29.1	29.9	27.9	24.0	20.6	26.9
Precip. (cm)	1.3	2.4	2.7	4.3	12.1	25.9	30.1	30.6	29.0	16.0	3.5	0.3	158.2
Cuiaba, Brazil, 15° 30 S; 165 m													
Temp. (°C)	27.2	27.2	27.2	26.6	25.5	23.8	24.4	25.5	27.7	27.7	27.7	27.2	26.5
Precip. (cm)	21.6	19.8	23.2	11.6	5.2	1.3	0.9	1.2	3.7	13.0	16.5	19.5	137.5

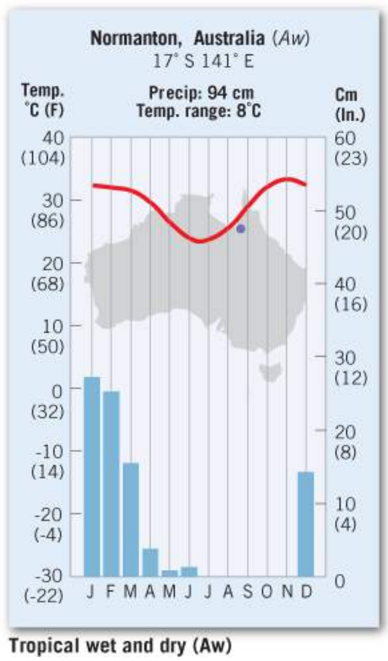
Because seasonal fluctuations in humidity and cloudiness are more pronounced in Aw areas, changes in daily temperature ranges are more pronounced during the year. Generally, temperature ranges are small during the rainy season, when humidity and cloud cover are at a maximum, and larger during dry periods, when clear skies and dry air prevail. Furthermore, because of the more persistent summertime cloudiness, many Aw stations experience their warmest temperatures at the end of the dry season, just prior to the summer solstice. Thus, in tropical wet and dry regions of the Northern Hemisphere, March, April, and May are often warmer than June and July.

Precipitation

The primary factor distinguishing the Aw climate from tropical wet climate (Af) is precipitation. Aw stations typically receive about 100 to 150 centimeters (40 to 60 inches) of rainfall each year, appreciably less than in the wet tropics. The most distinctive characteristic of this climate, however, is the *markedly seasonal variation in the amount of the rainfall*—wet summers followed by dry winters, as shown in Figure 15.8.

Figure 15.8 Tropical wet and dry climate

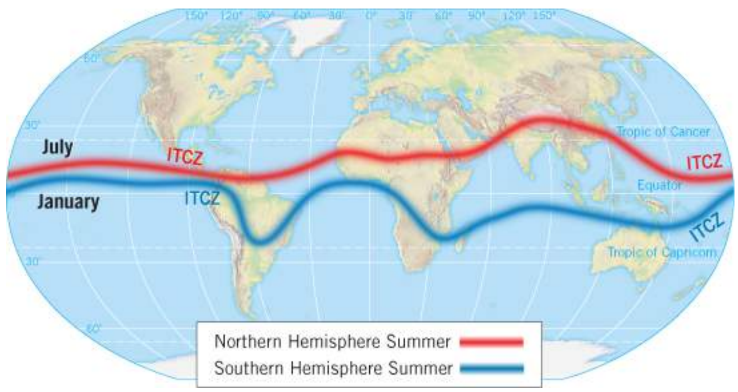
Aw stations such as Normanton, Australia, have an extended dry season.



The alternating wet and dry periods are tied to the shift in the zone of peak heating, which follows the Sun's seasonal migration north and south. The arrival of the zone of *maximum solar radiation* usually coincides with the position of the *equatorial low*, and it often coincides with the position of the *intertropical convergence zone (ITCZ)*. All of these factors bring changes in wind direction, moisture, and instability, as well as enhance low-level convergence that favors the development of rain and thunderstorms. Figure 15.9 illustrates how the ITCZ migrates with the vertical rays of the Sun from January to July. The zone of maximum heating and the equatorial low make similar seasonal migrations.

Figure 15.9 Migrating intertropical convergence zone (ITCZ)

The seasonal migration of the ITCZ strongly influences precipitation distribution in the tropics and subtropics.



Areas exhibiting Aw climates are found between the equator, with its convective rain showers, and the stable, subsiding air of the subtropical highs. Following the spring equinox, the advance of the zone of peak heating brings the summer rainy season—and weather patterns typical of the wet tropics. Later in the year, with the retreat of these conditions toward the equator, subtropical high pressure advances into the region and brings an extended arid period.

During this dry season, the landscape grows parched, and nature seems to go dormant as water-stressed trees shed their leaves and the abundant tall grasses turn brown and wither. The dry season's duration depends primarily on distance from the equator. Typically, the farther an Aw station is from the equator, the shorter the rainy season and the longer the locale will be influenced by the dry, stable conditions of a subtropical high. Consequently, the higher the latitude, the longer the dry season and the shorter the wet period.

Tropical Monsoon Climate (Am)

The **tropical monsoon climate (Am)** describes tropical areas that experience a pronounced seasonal shift in wind pattern. This shift in the wind pattern, in turn, produces a seasonal change in rainfall amounts. Recall that the term **monsoon** refers to wind systems that have a distinctive seasonal reversal of direction (see Figure 7.11). Summer rainfall occurs when humid, unstable air moves from the ocean over land. In winter, this pattern reverses, and dry winds that originate over the continent blow toward the sea.

The tropical monsoon climate is found mainly on the windward coasts of landmasses. Locations that experience this climate type include coastal India, Myanmar (formally Burma), northeastern Australia, northeastern South America, and the Philippines (see Figure 15.4). In areas where highlands exist, orographic lifting can substantially increase rainfall amounts.

> The tropical monsoon climate (Am) is found mainly on the windward coasts of landmasses, particularly in tropical Southeast Asia.

Temperature

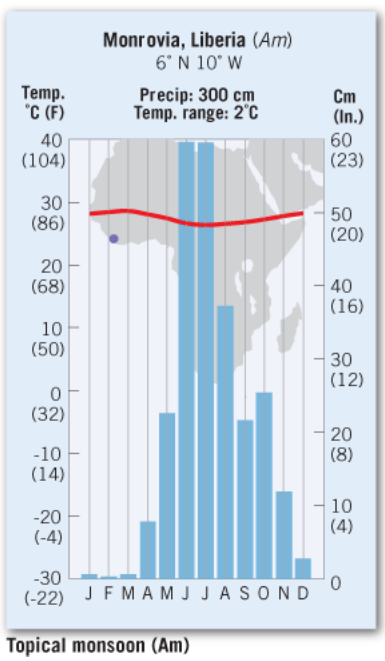
Average temperatures tend to be only slightly less than the wet tropics (Af). However, the warmest months usually occur in late spring before the arrival of the rainy season, when cloud cover reduces the amount of solar heating.

Precipitation

The climograph in Figure 15.10 illustrates the characteristics of the tropical monsoon climate. Notice the enormous amount of rainfall associated with the summer monsoon. Although the precipitation pattern for the Am climate is similar to that for the tropical wet and dry climate (Aw), the tropical monsoon climate is more extreme—particularly in the warm summer months, when rainfall amounts can be staggering. It is not uncommon to have more than 75 centimeters (30 inches) of precipitation in two or three of the summer months. In fact, many Am stations receive more annual rainfall than stations in the wet tropics (Af). By contrast, meager rainfall is the rule in the winter.

Figure 15.10 Tropical monsoon climate

Monrovia, Liberia, has a short dry season that contrasts sharply with its rainy season.



The tropical monsoon climate (Am) is dominated by alternating periods of rainfall and drought associated with the monsoon—wind systems with a pronounced seasonal reversal of direction.

Monsoon Circulation

Monsoon circulation develops mainly in response to differences in annual temperature variations between continents and oceans. Summer heating generates an area of thermally induced low pressure over the interior of the continents. This low is further strengthened by the poleward advance of the ITCZ (see Figure 15.9). Thus, the *summertime* circulation is from higher pressure over the ocean, which carries warm humid air toward the lower pressure over the continent. As winter approaches, winds reverse direction as a strong high-pressure system develops over the chilled continent and the ITCZ migrates equatorward. By *midwinter*, dry winds blow from the continent, bringing the dry season, when some months may be rainless.

It should be noted that monsoon circulation and its associated rainfall pattern affects regions outside the tropics—mainly some areas within the mild midlatitude climate type. Monsoon circulation can also influence the precipitation pattern in some arid regions.

Concept Checks 15.2

- How does a tropical rain forest differ from a typical middle-latitude forest?
- What is another name for the tropical wet and dry (Aw) climate?
- Briefly describe the tropical monsoon climate.

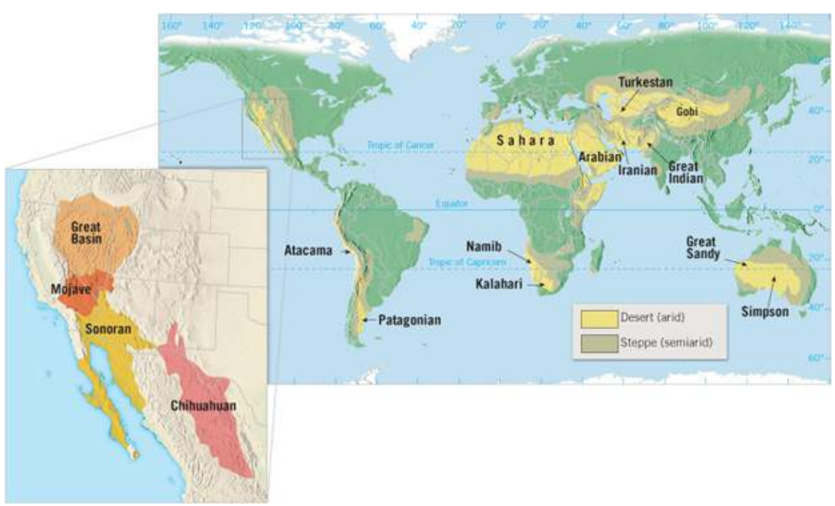
15.3 The Dry Climates (B)

LO 3 Contrast low-latitude dry climates and middle-latitude dry climates.

The dry regions of the world cover about 30 percent of Earth's land surface—the largest climate zone (Figure 15.11). The characteristic feature of *dry climates (B)* is meager and unreliable rainfall. Generally, the smaller the mean annual rainfall, the greater its variability. As a result, yearly rainfall averages are often misleading. For example, during one 7-year period, Trujillo, Peru, had an average annual rainfall of 6.1 centimeters (2.4 inches). A closer look reveals that during the first 6 years and 11 months of the period, the station received a scant 3.5 centimeters (1.4 inch). Then, during the 12th month of the 7th year, 39 centimeters (15.2 inches) of rain fell, more than half of it falling during a 3-day span.

Smartfigure 15.11 **Dry (B) climates**

Arid and semiarid climates cover about 30 percent of Earth's land surface. The dry region of the American West is commonly divided into four deserts, two of which extend into Mexico.



Watch **SmartFigure: Deserts**

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> The characteristic feature of dry climates (B) is meager and unreliable rainfall.

This extreme case illustrates the irregularity of rainfall in most dry regions—the occasional wet period tends to lift the average. Thus, most dry regions are inhabited by drought-tolerant plants adapted to uncertain precipitation.

What Is Meant by "Dry"?

Climatologists define *dry climates (B)* as those in which the *yearly precipitation is less than the potential water loss by evaporation.* Dryness, then, is not only related to annual rainfall, but also a function of evaporation, which in turn depends closely on temperature. As temperatures climb, potential evaporation increases as well.

For example, 25 centimeters (10 inches) of precipitation is sufficient to support forests in northern Scandinavia, where evaporation is low because of cool temperatures and moist air. However, the same amount of rain falling on Nevada or Iran supports only a sparse vegetative cover because the rate of evaporation into the hot, dry air is high. Clearly, no specific amount of precipitation can define a dry climate.

To establish a meaningful boundary between dry and humid climates, the Köppen classification uses formulas that involve three variables: (1) average annual precipitation, (2) average annual temperature, and (3) seasonal distribution of precipitation. In addition to the amount of precipitation, temperature is an important factor because it contributes to evaporation. The amount of rainfall defining the humid–dry boundary is greater where temperatures are high and less where temperatures are low. The last variable, the seasonal distribution of precipitation, is also important. If rain is concentrated in the warmest months, loss to evaporation is greater than if it is concentrated in the cooler months.

Table 15.2 summarizes these differences. For example, to be classified as *humid*, a station with an annual mean temperature of 20°C (68°F) and a summer wet season must receive more than 68 centimeters (26.5 inches) of precipitation per year. If less than 68 centimeters are received, the station is classified as *dry*. By contrast, if the rain falls primarily in winter, a station that receives only 40 centimeters (15.6 inches) is considered humid. If the precipitation occurs more consistently throughout the year, the amount of precipitation that defines the humid–dry boundary is 54 centimeters, as shown in Table 15.2.

Table 15.2 Average Annual Precipitation at the Humid–Dry Boundary

Average Annual Temperature (°C)	Average Annual Precipitation Summer Wet (cm)	Even Distribution (cm)	Winter Wet (cm)
5	38	24	10
10	48	34	20
15	58	44	30
20	68	54	40
25	78	64	50
30	88	74	60

Based on water deficiency data, there are two major dry climatic types: **desert, or arid (BW)**, and **steppe, or semiarid (BS)**. Deserts and steppes have many features in common; their differences are primarily a matter of degree. A steppe is a more humid variant of a desert and represents a transition zone that surrounds a desert, separating it from the bordering humid climates.

In addition, deserts and steppes are divided based on latitude into *subtropical* and *middle latitude deserts* and *steppes*. As these names imply, subtropical deserts and steppes have hot summers and mild winters, whereas midlatitude deserts and steppes have hot summers and comparatively cold winters.

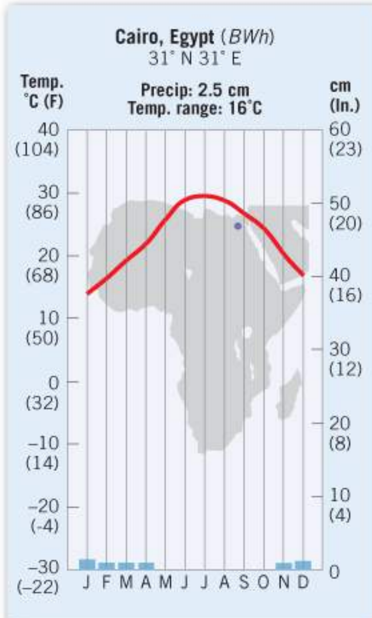
Subtropical Desert (BWh) and Steppe (BSh)

The subtropical dry climates are located largely between 15° and 30° latitude, centered on the Tropic of Cancer and the Tropic of Capricorn. Figure 15.11 reveals a virtually unbroken desert environment stretching more than 9300 kilometers (nearly 6000 miles) from North Africa to the dry lands of northwestern India. In addition to this single great expanse, the Northern Hemisphere contains another, much smaller, area of **subtropical desert (BWh)** and **subtropical steppe (BSh)** in northern Mexico and the southwestern United States. In the Southern Hemisphere, dry climates dominate Australia, nearly 40 percent of which is desert, and much of the remainder is steppe. In addition, arid and semiarid areas exist in southern Africa and make a rather limited appearance in coastal Chile and Peru. The distribution of these dry subtropical climates is primarily a consequence of subsidence and stability of the large subtropical highs located over the adjacent oceans (see Figure 7.11).

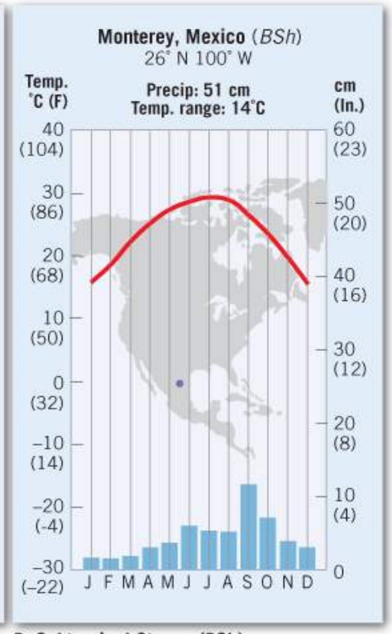
> Dominated by subtropical highs, the subtropical desert (BWh) and steppe (BSh) climates lie near the Tropic of Cancer and the Tropic of Capricorn.

Figure 15.12 presents climographs for both a subtropical desert and a subtropical steppe. Note that both stations experience hot summers and mild winters. The most significant difference between these climates is not temperature, but the total amount of precipitation and its distribution —significantly less rain falls, and does so more sporadically, in desert environments than in steppes.

Figure 15.12 **Climographs for representative subtropical deserts and steppes**



A. Subtropical Desert (BWh)



B. Subtropical Steppe (BSh)

You might have wondered . . .

I heard somewhere that deserts are expanding. Is that actually occurring?

Yes. The process is called *desertification*, a term that refers to the alteration of land to desertlike conditions as a result of human activities. It commonly takes place on the margins of deserts and is primarily triggered by plowing or overgrazing that removes the sparse natural vegetation in marginal areas. When drought occurs, as it inevitably does in these transition zones, and the vegetative cover falls below the minimum required to hold the soil against erosion, the destruction becomes irreversible. Desertification is occurring in many places but is particularly serious in the region south of the Sahara Desert known as the Sahel.

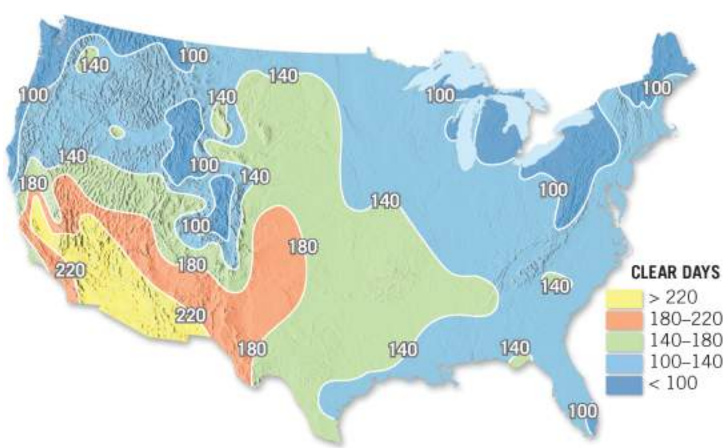
Temperature

Notice in Figure 15.12 that the midsummer temperatures at Cairo, Egypt, and Monterey, Mexico, are hot, averaging about 30°C (86°F). This is the consequence of the their low-latitude locations, where near-vertical rays of the Sun and clear skies result in blistering daytime temperatures that are significantly hotter than other tropical locations. By contrast, winter temperatures are mild, generally above 15°C (59°F).

Daily temperature changes in subtropical desert environments are controlled largely by the lack of humidity and cloud cover in these areas of subsidence. Desert skies are almost always clear. Yuma, Arizona, for example, receives an average of 91 percent of possible sunshine (Figure 15.13). Clear skies coupled with low humidity allow abundant solar radiation to reach the ground during the day and permit the rapid exit of terrestrial radiation at night.

Figure 15.13 Average annual number of clear days

With few exceptions, desert skies are typically cloudless and hence receive a very high percentage of the possible sunlight. This is strikingly illustrated in the U.S. Southwest desert.



Another factor contributing to high daytime ground temperatures is that very little solar energy is used for evaporation. Thus, almost all the energy goes to heating Earth's surface, which then heats the air above. By contrast, in humid regions significant solar energy is used to evaporate surface water, leaving less to heat the ground.

At night, temperatures typically drop rapidly because the air is dry and skies are clear. Consequently, subtropical deserts in the interiors of continents have the greatest daily temperature ranges on Earth. Daily summertime ranges of 25°C (45°F) are not uncommon and occasionally exceed those values. The highest daily temperature range ever recorded occurred at Salah, Algeria, in the Sahara Desert on October 13, 1927, where a 24-hour range of 55.5°C (100°F), from 52.2° to –3.3°C (126° to 26°F) was measured.

Precipitation

Within subtropical deserts, scant precipitation is both infrequent and erratic (Figure 15.12). These conditions exist because the areas are too far poleward to be influenced by the ITCZ and equatorial low, but too far from the middle latitudes to benefit from frontal and cyclonic precipitation. Even during summer, when daytime heating produces a steep environmental lapse rate and considerable convection, clear skies still rule. This is the result of subsidence aloft, which produces a lid, preventing air near the surface, with its modest moisture content, from rising high enough to condense and form clouds.

> Within subtropical deserts, the scant precipitation is both infrequent and erratic.

In the semiarid belts that surrounding deserts, the situation is less extreme because a seasonal rainfall pattern supports more vegetation. As shown by the data for Dakar in Table 15.3, steppe areas located on the equatorward side of a subtropical desert have a brief period of relatively heavy rainfall during the summer, when the ITCZ is farthest poleward. For steppe areas on the poleward margins of the subtropical deserts, the timing is reversed. As the data for Marrakech illustrates (Table 15.3), nearly all precipitation falls during the cool season, when middle-latitude cyclones often take more equatorward routes and bring occasional periods of rain.

Table 15.3 Data for Subtropical Steppe and Desert Stations

	J	F	M	A	M	J	J	A	S	O	N	D	YR
Marrakech, Morocco, 31° 37 N; 458 m Semitropical steppe (BSh)													
Temp. (°C)	11.5	13.4	16.1	18.6	21.3	24.8	28.7	28.7	25.4	21.2	16.5	12.5	19.9
Precip. (cm)	2.8	2.8	3.3	3.0	1.8	0.8	0.3	0.3	1.0	2.0	2.8	3.3	24.2
Dakar, Senegal, 14° 44 N; 23 m Semitropical steppe (BSh)													
Temp. (°C)	21.1	20.4	20.9	21.7	23.0	26.0	27.3	27.3	27.5	27.5	26.0	25.2	24.5
Precip. (cm)	0	0.2	0	0	0.1	1.5	8.8	24.9	16.3	4.9	0.5	0.6	57.8
Alice Springs, Australia, 23° 38 S; 570 m Semitropical desert (BWh)													
Temp. (°C)	28.6	27.8	24.7	19.7	15.3	12.2	11.7	14.4	18.3	22.8	25.8	27.8	20.8
Precip. (cm)	4.3	3.3	2.8	1.0	1.5	1.3	0.8	0.8	0.8	1.8	3.0	3.8	25.2

Table 15.3 also illustrates that "dryness" is not only related to annual rainfall, but also a function of evaporation. Notice that Alice Springs, Australia, gets slightly more precipitation than does Marrakech. However, Alice Springs is classified as arid (desert) whereas Marrakech is classified as semiarid—a steppe. The reason for this difference is the timing of the arrival of the precipitation. The wettest months in Alice Springs are December, January, and February, which is summer in the Southern Hemisphere. Marrakech, by contrast, reaches its peak rainfall during the winter, when the rate of evaporation is slowest.

West Coast Subtropical Deserts

Where subtropical deserts are found along the west coasts of continents, cold ocean currents have a dramatic influence on the climate. The principal west coast deserts are the Atacama in South America and the Namib in southern and southwestern Africa (see Figure 15.11). Other areas include portions of the Sonoran Desert in Baja, California, and coastal areas of the Sahara in northwestern Africa.

West coast subtropical deserts deviate considerably from the general image we have of deserts. The most obvious effect of these cold currents is reduced temperatures, as exemplified by the data for Lima, Peru, and Port Nolloth, South Africa (Table 15.4). Compared with other stations at similar latitudes, these places have lower annual mean temperatures and are often called *mild subtropical deserts*. Port Nolloth, for example, has an annual mean of 14°C (57°F), which is much cooler than inland stations of the same climate type (Table 15.4). Although these stations are adjacent to oceans, their yearly rainfall totals are among the lowest in the world. The aridity of these coasts is intensified because air above the cold offshore waters is chilled, which further stabilizes already dry air.

Table 15.4 Data for West Coast Tropical Desert Stations

	J	F	M	A	M	J	J	A	S	O	N	D	YR
Port Nolloth, South Africa, 29° 14 S; 7 m													
Temp. (°C)	15.0	16.0	15.0	14.0	14.0	13.0	12.0	12.0	13.0	13.0	15.0	15.0	14.0
Precip. (cm)	0.3	0.3	0.5	0.5	1	0.8	1	0.8	0.5	0.3	0.3	0	6.3
Lima, Peru, 12° 02 S; 155 m													
Temp. (°C)	22.0	23.0	23.0	21.0	19.0	17.0	16.0	16.0	16.0	17.0	19.0	21.0	19.0
Precip. (cm)	0.2	T	T	T	0.5	0.5	0.8	0.8	0.8	0.3	0.32	T	4.1

> West coast subtropical deserts deviate considerably from the general image we have of subtropical deserts because of the effect of nearby cold ocean currents, which reduces temperatures.

In addition, the air above these cold currents frequently reaches its dew point, generating a layer of fog. When these humid cool air masses move over the adjacent coastal areas, they bring high relative humidity, abundant advection fog, and, sometimes, dense stratus cloud cover.

Chile's Atacama Desert: Driest of the Dry

Stretching for nearly 1000 kilometers (600 miles) in northern Chile, the Atacama Desert is situated between the Pacific Ocean on the west and the towering Andes Mountains on the east (see Figure 15.11). This slender arid zone extends inland an average distance of about 70 kilometers (50 miles).

The Atacama has the distinction of being the world's driest desert. In many places, measurable rain occurs only at intervals of several years. At Arica, a coastal town near Chile's border with Peru, the average annual rainfall is a mere 0.05 centimeter (0.02 inch). Further inland, some stations have *never* recorded rainfall. The Atacama Desert owes its extreme aridity to its location near the cold Peru Current, which flows northward along the coast, chilling and stabilizing the lower atmosphere (see Figure 7.24).

Midlatitude Desert (BWk) and Steppe (BSk)

Unlike their tropical counterparts, **midlatitude deserts (BWk)** and **midlatitude steppes (BSk)** are not controlled by the subsiding air masses of the subtropical highs. Instead, these dry lands exist principally because of their position in the deep interiors of large landmasses, far removed from the main moisture source—the oceans. In addition, the presence of high mountains across the paths of the prevailing winds further separates these areas from water-bearing maritime air masses (see Figure 4.17). In North America, the Coast Ranges, Sierra Nevada, and Cascades are the foremost barriers; in Asia, the great Himalayan chain prevents the summertime monsoon flow of moist air off the Indian Ocean from reaching into the interior.

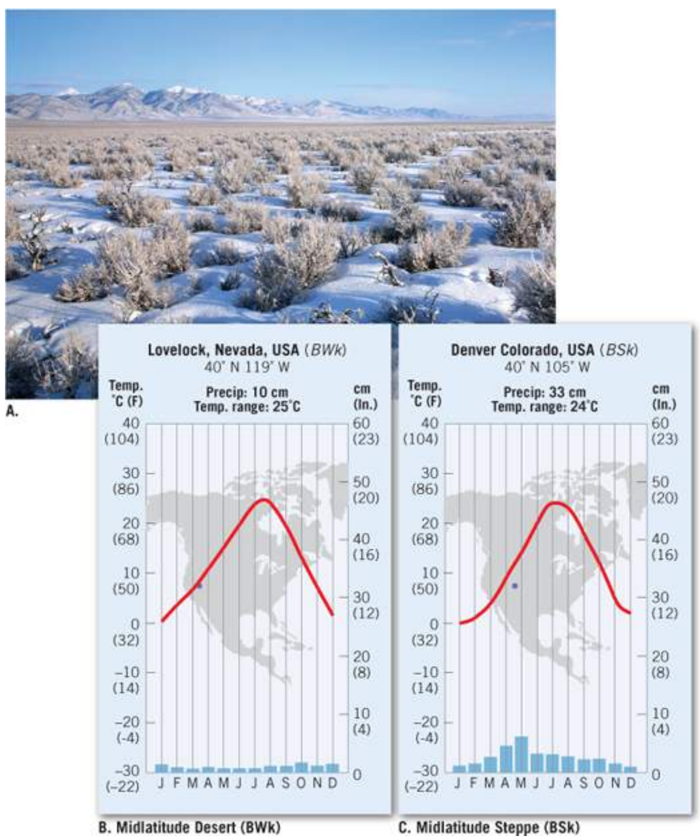
> Unlike their low-latitude counterparts, middle-latitude deserts (BWk) and steppes (BSk) exist principally because of their locations in the interiors of large landmasses.

A glance at Figure 15.11 reveals that midlatitude desert and steppe climates are most widespread in North America and Eurasia. The Southern Hemisphere lacks extensive land areas in the middle latitudes—the only exception being the Patagonian Desert, which formed in the rain shadow of the Andes.

Like subtropical deserts and steppes, the dry regions of the middle latitudes have meager and unreliable precipitation. Most, but not all, midlatitude arid and semiarid stations have a summer precipitation maximum, because in winter, high pressure and cold temperatures that oppose uplift and precipitation tend to dominate the continents. In summer, however, conditions are somewhat more conducive to cloud formation and precipitation because high pressure over the continents disappears and airflow from the moist ocean toward land dominates the atmospheric circulation. Unlike the subtropical dry areas, however, these more poleward regions have much colder winter temperatures and, hence, lower annual temperature means and higher annual ranges. Because winter temperatures typically average below freezing, when precipitation occurs, it often falls as snow (Figure 15.14).

Figure 15.14 **Midlatitude deserts (BWk) and steppes (BSk)**

A. The Great Basin Desert is a rain shadow desert that covers nearly all of Nevada and portions of adjacent states. **B.** Climate data for Lovelock, Nevada, a midlatitude desert (BWk). **C.** Climate data for Denver, Colorado, a midlatitude steppe (BSk).



You might have wondered . . .

Aren't deserts mostly covered with sand dunes?

We envision deserts as mile after mile of drifting sand dunes. While it's true that sand accumulates and forms these striking features in some deserts, sand dunes represent only a small percentage of the world's total desert area. For example, in the Sahara—the world's largest desert—accumulations of sand cover only one-tenth of its area. The sandiest of all deserts is the Arabian, one-third of which consists of sand.

Concept Checks 15.3

1. Explain why the amount of precipitation defining the humid–dry boundary is variable.
2. What is the primary reason for the existence of arid subtropical climates?
3. What factor is the most important for generating middle-latitude deserts and steppes?

15.4 Mild Midlatitude Climates (C)

LO 4 Distinguish among the three categories of C climates.

The *mild midlatitude climates (C)* are a transition between warm tropical climates and midlatitude climates with severe winters. Whereas tropical climates are characterized by warm temperatures throughout the year, midlatitude climates have discernible summer and winter seasons.

Humid Subtropical Climate (Cfa)

The **humid subtropical climate (Cfa)** can be found on the eastern sides of the continents, in the 25° to 40° latitude range. The humid subtropics dominate the southeastern United States and include cities such as Atlanta, Georgia; New Orleans, Louisiana; and Charleston, South Carolina. Other similarly situated areas include portions of Argentina and southern Brazil in South America, eastern China and southern Japan in Asia, and the east coast of Australia (see Figure 15.3).

Temperature

A visitor to the humid subtropics in the summer would experience the kind of hot, sultry weather typical of the rainy tropics. Daytime temperatures that exceed 30°C (86°F) are common and occasionally reach 40°C (more than 100°F). Because the relative humidity is normally high, nighttime brings little relief. However, winter temperatures are markedly lower. This is to be expected because higher-latitude locations experience a wider variation in Sun angle and day length than tropical regions. Higher-latitude locations also experience more frequent invasions of continental polar (cP) air masses during winter.

Precipitation

During summer, afternoon or evening thunderstorms are possible and occur between 40 and 100 days each year. The primary reason for the abundance of afternoon thunderstorms is that during the summer months, maritime tropical (mT) air masses move inland from the warm subtropical waters adjacent to these landmasses. As the warm, moist air passes over the heated continent, it becomes increasingly unstable, giving rise to convectional showers and thunderstorms.

As summer turns to autumn, the humid subtropics lose their similarity to the rainy tropics. Although winters are mild, frost is common in higher-latitude Cfa areas. Winter precipitation is also different—typically appearing in the form of rain, freezing rain, and occasionally snow, which is generated along fronts associated with midlatitude cyclones that sweep over these regions.

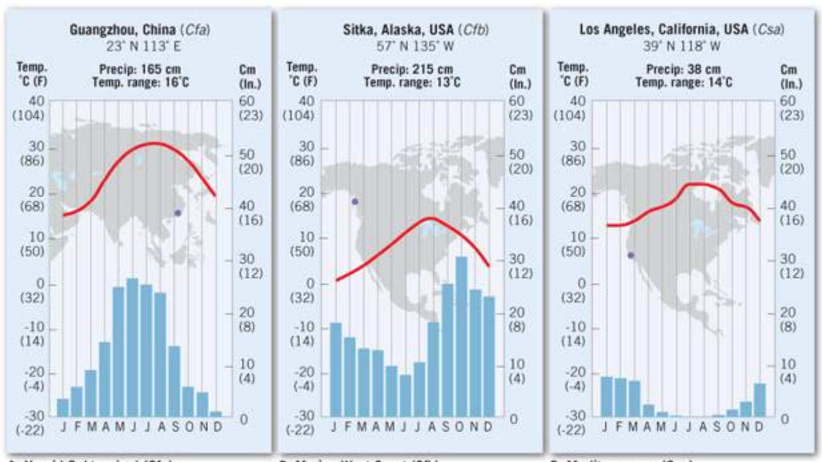
> Humid subtropical climate (Cfa) is characterized by hot, sultry summers and mild winters.

The data for two humid subtropical stations in Table 15.5 serve to summarize the general characteristics of the Cfa climate. Yearly precipitation usually exceeds 100 centimeters (39 inches), and the rainfall is abundant throughout the year. Although summer normally brings the most precipitation, there is considerable variation. In the United States, for example, precipitation along the Gulf coast is relatively evenly distributed. But as one moves poleward, much more precipitation falls in summer. In Asia, the well-developed monsoon circulation strongly favors a summer precipitation maximum (Figure 15.15A).

Table 15.5 **Data for Humid Subtropical Stations (Cfa)**

	J	F	M	A	M	J	J	A	S	O	N	D	YR
New Orleans, Louisiana, 29° 59 N; 1 m													
Temp. (°C)	12.0	13.0	16.0	19.0	23.0	26.0	27.0	27.0	25.0	21.0	15.0	13.0	20.0
Precip. (cm)	9.8	10.1	13.6	11.6	11.1	11.3	17.1	13.6	12.8	7.2	8.5	10.4	137.1
Buenos Aires, Argentina, 34° 35 S; 27 m													
Temp. (°C)	24.0	23.0	21.0	17.0	14.0	11.0	10.0	12.0	14.0	16.0	20.0	22.0	17.0
Precip. (cm)	10.4	8.2	12.2	9.0	7.9	6.8	6.1	6.8	8.0	10.0	9.0	8.3	102.7

Figure 15.15 **Climographs for selected mild midlatitude climate (C) stations**



A. Humid Subtropical (Cfa) B. Marine West Coast (Cfb) C. Mediterranean (Csa)

Marine West Coast Climate (Cfb)

On the western (windward) sides of continents from about 40° to 65° north and south latitude is a climate region dominated by the onshore flow of oceanic air. The prevalence of maritime air masses means mild winters, cool summers, and ample rainfall throughout the year. In North America, this **marine west coast climate (Cfb)** extends from near the U.S.–Canadian border northward as a narrow belt into southern Alaska (Figure 15.16). A similar slender strip occurs in South America along the coast of Chile. In both instances, high mountains parallel the coast and prevent the marine climate from penetrating far inland. The largest area of Cfb climate is in Europe, where there is no mountain barrier blocking the movement of cool maritime air from the North Atlantic (see Figure 15.3).

Figure 15.16 Marine west coast climate

As the name of this climate implies, the ocean exerts a strong influence, moderating temperatures and providing moisture that supports lush vegetation.

Temperature

The ocean is near, so winters are mild and summers are relatively cool. Therefore, a low annual temperature range is characteristic of the marine west coast climate. The western edge of North America is especially sheltered from incursions of frigid cP air by high mountains to the east, which makes cold weather rare. Because no such mountain barrier exists in Europe, cold waves there are more frequent.

Precipitation

The data for representative marine west coast stations in Table 15.6 reveal no pronounced dry period, but many locations experience noticeably less precipitation during the summer (Figure 15.15B). A comparison of precipitation data for London and Vancouver (Table 15.6) also demonstrates that coastal mountains have a significant influence on yearly rainfall. Vancouver has nearly twice the total rainfall as London. In settings like Vancouver's, precipitation totals are higher not only because of orographic uplift but also because the surrounding highlands slow the passage of cyclonic storms, allowing them to linger and drop a greater quantity of water.

Table 15.6 Data for Marine West Coast Stations (Cfb)

	J	F	M	A	M	J	J	A	S	O	N	D	YR
Vancouver, British Columbia, 49° 11 N; 0 m													
Temp. (°C)	2.0	4.0	6.0	9.0	13.0	15.0	18.0	17.0	14.0	10.0	6.0	4.0	10.0
Precip. (cm)	13.9	12.1	9.6	6.0	4.8	5.1	2.6	3.6	5.6	11.7	14.2	15.6	104.8
London, United Kingdom, 51° 28 N; 5 m													
Temp. (°C)	4.0	4.0	7.0	9.0	12.0	16.0	18.0	17.0	15.0	11.0	7.0	5.0	10.0
Precip. (cm)	5.4	4.0	3.7	3.8	4.6	4.6	5.6	5.9	5.0	5.7	6.4	4.8	59.5

> Marine west coast climate (Cfb) is dominated by maritime air masses that produce mild winters, cool summers, and ample rainfall throughout the year.

Mediterranean Climates (Csa, Csb)

The two Cs climates, most commonly termed **mediterranean climates (Csa, Csb)**, are also sometimes referred to as *dry-summer subtropical climates.* Mediterranean climates mainly occur along the west sides of continents between latitudes 30° and 45° (see Figure 15.3). Situated between the dry subtropical steppes on the equatorward side, and the humid marine west coast climates on the poleward side, this climate region is transitional in character.

In summer, this region is dominated by the stable eastern side of the oceanic subtropical highs, which bring clear skies and virtually no rain (Figure 15.15C). The modest annual precipitation therefore occurs in the winter. Thus, these areas alternate between being a part of the dry subtropics in summer and an extension of the west coast marine climates in winter.

Mountain ranges limit mediterranean climates to a relatively narrow coastal zone in both North and South America. The Australian and African continents barely extend to the latitudes where this climate type exists. Inland extension of this climate type occurs only in the Mediterranean basin, hence the name *mediterranean climate* (Figure 15.17). In this region, subsidence associated with the subtropical high extends far to the east in summer; in winter the Mediterranean Sea is a major route of cyclonic disturbances.

Figure 15.17 Italy's Tuscany region

The dry-summer subtropical climate is especially well developed in the Mediterranean region.

Temperature

Two types of mediterranean climates are recognized, based primarily on summertime temperatures. The *cool summer type (Csb)*, as exemplified by San Francisco, is limited to coastal areas where cool summer temperatures expected on a windward west coast are further intensified by cold ocean currents (Table 15.7).

Table 15.7 Data for Mediterranean Climate Stations (Csb, Csa)

	J	F	M	A	M	J	J	A	S	O	N	D	YR
San Francisco, California, 37° 37 N; 5 m Mediterranean, cool summers (Csb)													
Temp. (°C)	9.0	11.0	12.0	13.0	15.0	16.0	17.0	17.0	18.0	16.0	13.0	10.0	14.0
Precip. (cm)	10.2	8.8	6.8	3.3	1.2	0.3	0.0	0.1	0.5	1.9	4.0	10.4	47.5
Sacramento, California, 38° 35 N; 13 m Mediterranean, warm summers (Csa)													
Temp. (°C)	8.0	10.0	12.0	16.0	19.0	22.0	25.0	24.0	23.0	18.0	12.0	9.0	17.0
Precip. (cm)	8.1	7.6	6.0	3.6	1.5	0.3	0.0	0.1	0.5	2.0	3.7	8.2	41.6

> Mediterranean climates (Csa and Csb) are dominated by oceanic subtropical highs in summer, which produce dry conditions; in winter, frequent cyclonic storms produce a wet season.

The data for Sacramento, California, shown in Table 15.7, illustrates the features of the *warm summer type (Csa)* Mediterranean climate. Winter temperatures in Sacramento are similar to those in San Francisco. In summer, however, because of its location inland from the coast, Sacramento experiences temperatures that are noticeably *higher* than those in San Francisco. Thus, annual temperature ranges are higher in Csa climate areas as compared to Csb climate zones.

Precipitation

Yearly precipitation within the mediterranean climate zone ranges between about 40 and 100 centimeters (16 and 40 inches). Along the equatorward margins of this climate type, many stations barely escape being classified as semiarid. Los Angeles, for example, receives only 38 centimeters (15 inches) of precipitation annually, whereas San Francisco, 400 kilometers (250 miles) to the north, receives 51 centimeters (20 inches) per year. Still farther north, at Portland, Oregon, the yearly rainfall average is more than 90 centimeters (35 inches).

Concept Checks 15.4

- Describe and explain the differences between summertime and wintertime precipitation in the humid subtropics (Cfa).
- Why is the marine west coast climate (Cfb) represented by only slender strips of land in North and South America but extends far inland in Western Europe?
- Briefly describe mediterranean climate characteristics.

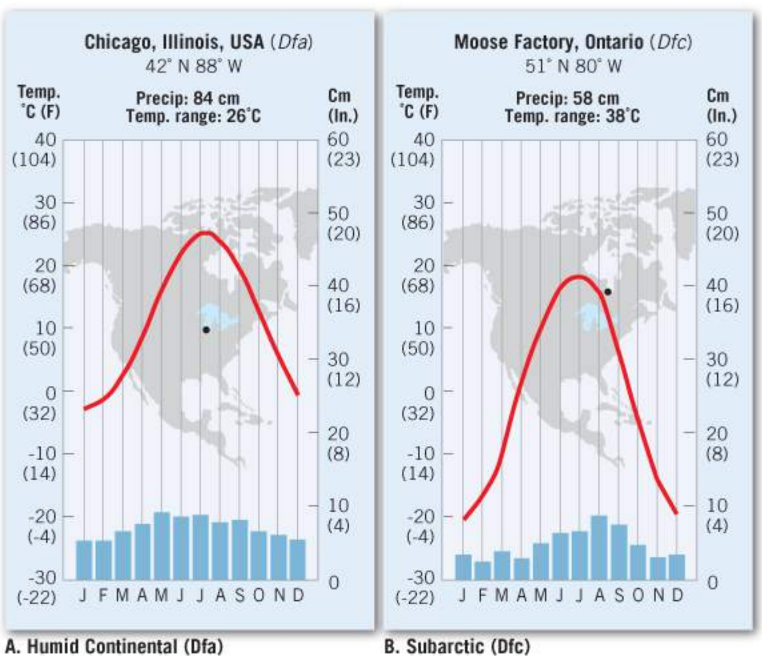
15.5 Midlatitude Climates with Severe Winters (D)

LO 5 Summarize the characteristics of the two categories of D climates.

Midlatitude climates with severe winters belong to the D group in the Köppen classification scheme. In this section, two types of D climates are discussed: the humid continental and the subarctic. Climographs for representative locations of both types are shown in Figure 15.18.

Figure 15.18 Climographs for selected stations in midlatitude climates with severe winters (D)

Climates in this category are associated with the interiors of large landmasses in the mid- to high latitudes of the Northern Hemisphere.



Humid Continental Climate (Dfa)

The **humid continental climate (Dfa)** is characteristic of large landmasses located in the midlatitudes. Because of this, Dfa climates are not found in the Southern Hemisphere, where midlatitudes are dominated by the ocean. Instead, it is confined to central and eastern North America and Eurasia in the 40° to 50° north latitude range (see Figure 15.3).

This climate region, dominated by the polar front, is thus a battleground for tropical and polar air masses—thereby generating traveling midlatitude cyclones. No other climate experiences such rapid and erratic changes in the weather. Cold waves, heat waves, blizzards, and heavy downpours are all yearly events in the humid continental realm.

> Humid continental climates (Dfa) are characterized as severe—cold winters and hot summers.

Temperature

Both winter and summer temperatures in the Dfa climate are relatively severe. For example, midsummer temperatures in Omaha, Nebraska, can exceed 35°C (95°F), whereas below-freezing winter temperatures are common. Consequently, annual temperature ranges in Dfa climate zones are large—as illustrated by the stations in Table 15.8.

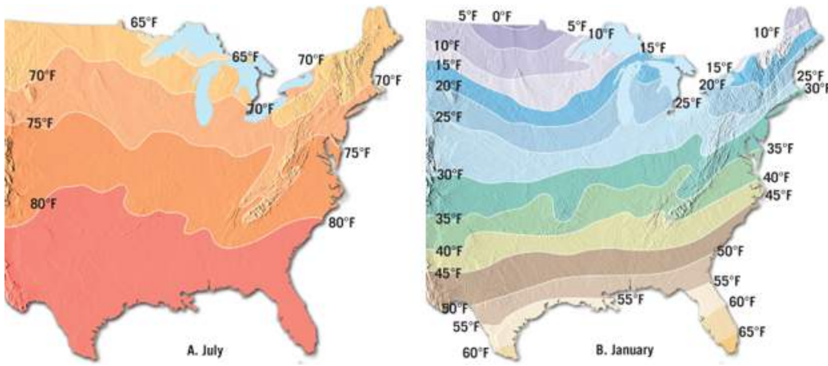
Table 15.8 Data for Humid Continental Stations (Dfa)

	J	F	M	A	M	J	J	A	S	O	N	D	YR
Omaha, Nebraska, 41° 18 N; 330 m													
Temp. (°C)	–6.0	–4.0	3.0	11.0	17.0	22.0	25.0	24.0	19.0	12.0	4.0	–3.0	10.0
Precip. (cm)	2.0	2.3	3.0	5.1	7.6	10.2	7.9	8.1	8.6	4.8	3.3	2.3	65.2
New York, New York, 40° 47 N; 40 m													
Temp. (°C)	–1.0	–1.0	3.0	9.0	15.0	21.0	23.0	22.0	19.0	13.0	7.0	1.0	11.0
Precip. (cm)	8.4	8.4	8.6	8.4	8.6	8.6	10.4	10.9	8.6	8.6	8.6	8.4	106.5
Winnipeg, Canada, 49° 54 N; 240 m													
Temp. (°C)	–18.0	–16.0	–8.0	3.0	11.0	17.0	20.0	19.0	13.0	6.0	–5.0	–13.0	3.0
Precip. (cm)	2.6	2.1	2.7	3.0	5.0	8.1	6.9	7.0	5.5	3.7	2.9	2.2	51.7
Harbin, Manchuria, 45° 45 N; 143 m													
Temp. (°C)	–20.0	–16.0	–6.0	6.0	14.0	20.0	23.0	22.0	14.0	6.0	–7.0	–17.0	3.0
Precip. (cm)	0.4	0.6	1.7	2.3	4.4	9.2	16.7	11.9	5.2	3.6	1.2	0.5	57.7

Although summertime temperatures in the northern parts of this climate zone are cooler than in the south, they are not markedly different. The summer map has only a few widely spaced isotherms, indicating a weak summer temperature gradient (Figure 15.19A). The winter map, however, shows temperatures decrease rapidly with increasing latitude (Figure 15.19B). This is confirmed in Table 15.8, which reveals that the temperature difference between Omaha and Winnipeg is more than twice as great in winter as in summer.

Figure 15.19 Temperatures in the eastern United States

A. During the summer months, north–south temperature variations in the eastern United States are small—that is, the temperature gradient is weak. **B.** In winter, however, north–south temperature contrasts are more extreme.



Precipitation

Table 15.8 also shows the general precipitation pattern for Dfa climates. A summer precipitation maximum occurs at each station, but it is weakly defined at New York because the east coast is more accessible to maritime air masses throughout the year. For the same reason, New York also has the highest total of the four stations. Harbin, Manchuria, on the other hand, shows the most pronounced summer maximum, followed by a winter dry season. This is characteristic of most eastern Asian stations and reflects the powerful control of the monsoon.

The data also reveal that precipitation generally decreases toward the continental interior primarily because of increasing distance from the sources of mT air. Furthermore, the more northerly stations are also influenced for a greater part of the year by drier polar air masses.

Winter precipitation is chiefly associated with the passage of fronts connected with traveling midlatitude cyclones. Part of the winter precipitation is snow, and as you might expect, the proportion of snowfall increases with latitude.

Subarctic Climates (Dfc, Dfd)

North of the humid continental climate is an extensive region of **subarctic climates (Dfc, Dfd)** consisting of broad, uninterrupted expanses in North America (western Alaska to Newfoundland) and in Eurasia (Norway to the Pacific coast of Russia). Often called the **taiga climate**, it closely corresponds to the northern coniferous forest region of the same name (Figure 15.20). Although they are scrawny, the spruce, fir, larch, and birch trees in the taiga represent the largest stretch of continuous forest on Earth.

Figure 15.20 Subarctic climate, also called taiga climate

This climate type takes its name from the Russian word for its northern coniferous forest.

Subarctic climates (Dfc and Dfd), often called *taiga climates* because they correspond to the northern coniferous forests of the same name, are situated north of the humid continental climates.

Temperature

The subarctic is illustrated by the data for Yakutsk, Russia, and Dawson, Yukon Territory, in Table 15.9. These data also show that the North American subarctic climate is less severe than that of northern Asia. Winter minimum temperatures are bitterly cold and among the lowest recorded outside the ice caps of Greenland and Antarctica. In fact, for many years the world's coldest temperature was attributed to Verkhoyansk in east-central Siberia, where the temperature dropped to −68°C (−90°F) on February 5 and 7, 1892.

Table 15.9 Data for Subarctic Stations (Dfc, Dfd)

	J	F	M	A	M	J	J	A	S	O	N	D	YR
Yakutsk, Russia, 62° 05 N; 103 m													
Temp. (°C)	−43.0	−37.0	−23.0	−7.0	7.0	16.0	20.0	16.0	6.0	−8.0	−28.0	−40.0	−10.0
Precip. (cm)	0.7	0.6	0.5	0.7	1.6	3.1	4.3	3.8	2.2	1.6	1.3	0.9	21.3
Dawson, Yukon Territory, Canada, 64° 03 N; 315 m													
Temp. (°C)	−30.0	−24.0	−16.0	−2.0	8.0	14.0	15.0	12.0	6.0	−4.0	−17.0	−25.0	−5.0
Precip. (cm)	2.0	2.0	1.3	1.8	2.3	3.3	4.1	4.1	4.3	3.3	3.3	2.8	34.6

In contrast, subarctic summers are remarkably warm, despite their short duration. When compared to regions farther south, however, this short season must be characterized as cool. Despite the many hours of daylight, the Sun never rises very high in the sky, so solar radiation is not intense. The extremely cold winters and relatively warm summers of the subarctic combine to produce the largest annual temperature ranges on Earth. Yakutsk, Russia holds the distinction of having an average temperature range of 63°C (113°F)—a record.

> The extremely cold winters and relatively warm summers of the subarctic combine to produce the largest annual temperature ranges on Earth.

Precipitation

Because these far northerly continental interiors are far removed from the influence of moist maritime air masses, only limited moisture is available throughout the year. Precipitation totals are therefore small, seldom exceeding 50 centimeters (20 inches). By far the greatest precipitation comes as rain from scattered summer convectional showers. Less snow falls in this area than in the humid continental climate to the south, yet lack of melting makes the entire winter accumulation visible, giving the illusion of more. Furthermore, during blizzards, high winds swirl the dry, powdery snow into high drifts, giving the false impression that more snow is falling than is actually the case.

Concept Checks 15.5

- Why is the humid continental climate confined to the Northern Hemisphere?
- Why do coastal stations such as New York City experience primarily continental climatic conditions?
- Describe and explain the annual temperature range one should expect in the subarctic climate zone.

15.6 Polar Climates (E)

LO 6 Contrast tundra and ice cap climates.

Just as the tropics are defined by their year-round warmth, so the polar realm is known for its enduring cold, with the lowest annual mean temperatures on the planet. Because polar winters are periods of perpetual night, or nearly so, temperatures are understandably bitter. During the summer, temperatures remain cool despite the long days because the Sun is so low in the sky that its oblique rays produce little warming. In addition, much solar radiation is reflected by the ice and snow or is used in melting the snow cover. In either case, energy that could have warmed the land is lost.

Although polar climates are classified as humid, precipitation is generally meager, with many nonmarine stations receiving less than 25 centimeters (10 inches) annually. Evaporation, of course, is also low. The scant precipitation is easily understood considering the temperature characteristics of the region—the amount of water vapor in the air is always minimal because cold air has a low capacity to hold moisture. Therefore, precipitation is usually most abundant during the warmer summer months, when the air's moisture content is highest.

According to the Köppen classification, *polar climates (E)* are those in which the mean temperature of the warmest month is below 10°C (50°F). Two types are recognized: the *tundra climate (ET)* and the *ice cap climate (EF)*.

The Tundra Climate (ET)

The **tundra climate (ET)** is found almost exclusively in the Northern Hemisphere. It occupies the coastal fringes of the Arctic Ocean, many Arctic islands, and the ice-free shores of northern Iceland and southern Greenland. In the Southern Hemisphere, no extensive land areas exist in the latitudes where tundra climates prevail. Consequently, except for some small islands in the southern oceans, the ET climate occupies only the southwestern tip of South America and the northern portion of the Palmer Peninsula in Antarctica.

The 10°C (50°F) isotherm for the warmest month marks the poleward limit of tree growth. Thus, the **tundra** is a treeless region of grasses, sedges, mosses, and lichens (Figure 15.21A). During the long cold season, plant life is dormant, but once the short, cool summer commences, these plants mature and rapidly produce seeds.

Figure 15.21 **Tundra climate (ET)**

A. Autumn colors of the tundra in Denali National Park, Alaska. **B.** Climograph representing a tundra (ET) climate.

A.

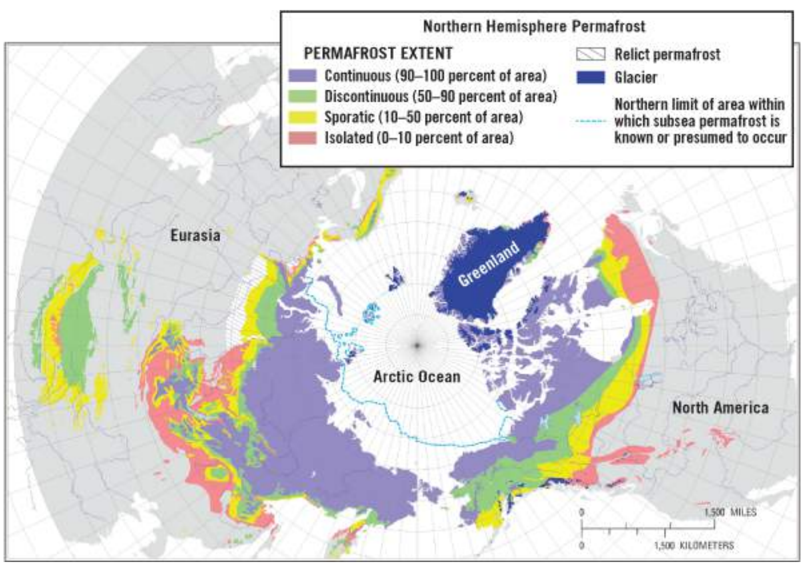
B. Tundra (ET)

The data for Point Barrow, Alaska (Figure 15.21B), on the shores of the frozen Arctic Ocean, illustrate a classic tundra climate. The combination of high latitude and the influence of a large landmass makes winters severe, makes summers cool, and produces wide annual temperature ranges. Yearly precipitation is low, with a modest summertime maximum.

Large portions of the tundra are characterized by **permafrost**, ground that remains frozen year-round (Figure 15.22). Because summers are cool and short, the frozen soils of the tundra generally thaw to depths of less than 1 meter (3 feet). When the activities of people disturb the surface, such as by removing the insulating vegetation mat or by constructing roads and buildings, the delicate thermal balance is disturbed, and the permafrost can thaw. Thawing produces unstable ground that may slide, slump, subside, and undergo severe frost heaving. When a heated structure is built directly on ice-rich permafrost, thawing creates soggy material into which the structure can sink.

Figure 15.22 Distribution of permafrost in the Northern Hemisphere

Permafrost underlies more than 80 percent of Alaska and about 50 percent of Canada.



The tundra climate (ET), marked by the 10°C (50°F) summer isotherm at its equatorward limit, is a treeless region of grasses, mosses, and lichens with permanently frozen subsoil, called *permafrost*.

The Ice-Cap Climate (EF)

The **ice-cap climate (EF)** has no monthly mean above 0°C (32°F). Because the average temperature for all months is below freezing, vegetation is absent, and the landscape is one of perpetual ice and snow. It covers a surprisingly large area of more than 15.5 million square kilometers (6 million square miles), or about 9 percent of Earth's land area (Figure 15.23). Aside from scattered occurrences in high mountain areas, it is largely confined to the ice sheets of Greenland and Antarctica.

Figure 15.23 Ice-cap climate (EF)

Greenland and Antarctica are the major examples of this extreme climate.

Watch Video: Operation IceBridge in Greenland

> The ice-cap climate (EF) does not experience any monthly mean temperatures above 0°C (32°F), prohibiting the growth of vegetation.

Average annual temperatures in EF regions are extremely low. For example, the annual mean at Eismitte, Greenland is −29°C (−20°F); at Byrd Station, Antarctica, −21°C (−6°F); and at Vostok, the Russian Antarctic Meteorological Station, −57°C (−71°F). Vostok also experienced the lowest temperature ever recorded, −88.3°C (−127°F), on August 24, 1960.

In addition to latitude, the primary reason for such low temperatures is the presence of permanent ice. Ice has a very high albedo, reflecting up to 80 percent of the meager sunlight that strikes it. The energy not reflected is largely used to melt the ice and thus is not available for raising the air temperature.

Another factor at many EF stations is elevation. Eismitte, at the center of the Greenland ice sheet, is almost 3000 meters (10,000 feet) above sea level, and much of Antarctica is even higher. Thus, permanent ice and high elevations further reduce the already low temperatures of the polar realm.

Concept Checks 15.6

■ What climate type in the Köppen classification scheme is characterized by its warmest monthly mean temperature of less than 10°C (50°F)?

■ Describe the tundra landscape.

■ Where are ice-cap climates (EF) developed most extensively?

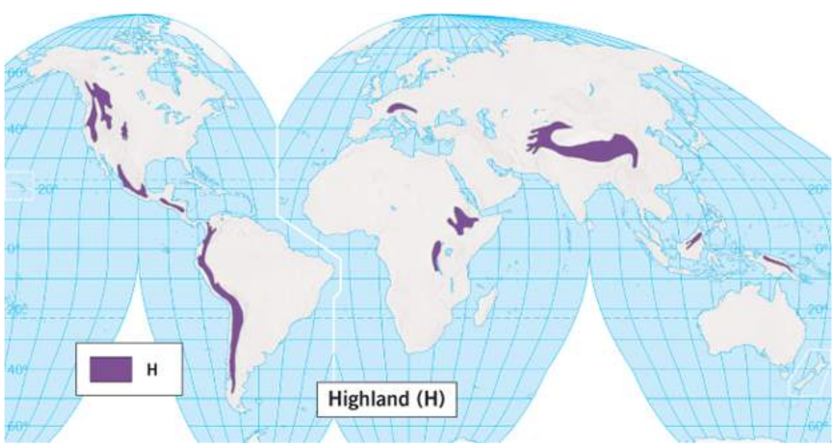
15.7 Highland Climates (H)

LO 7 List the characteristics of highland climates.

Locations with *highland climates (H)* are cooler and usually wetter than those in adjacent lowlands. World climate types already discussed consist of large, relatively homogeneous regions, whereas highland climates are characterized by a great diversity of climatic conditions over small areas.

In North America, highland climates characterize the Rockies, Sierra Nevada, Cascades, and the mountains and interior plateaus of Mexico. In South America, the Andes create a continuous band of highland climate that extends for nearly 8000 kilometers (5000 miles). The greatest span of highland climates stretches from western China, across southern Eurasia, to northern Spain, from the Himalayas to the Pyrenees (Figure 15.24). Highland climates in Africa occur in the Atlas Mountains in the north and in the Ethiopian Highlands in the east.

Figure 15.24 The global distribution of highland climates (H)



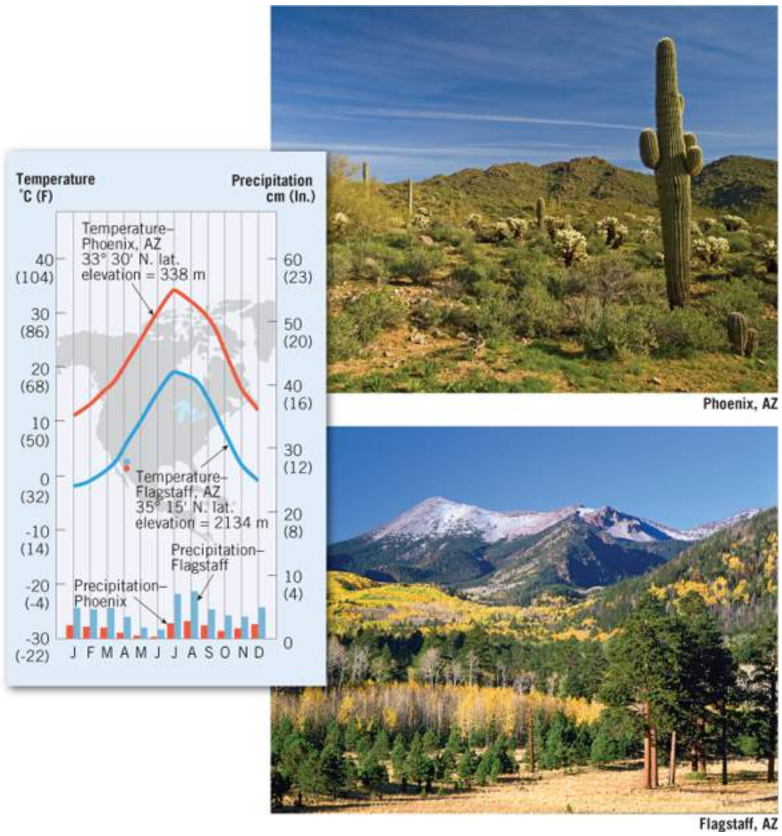
> Highland climates are characterized by a great diversity of climatic conditions across small areas.

The best-known climate effect of increased altitude is lower temperatures. Greater precipitation due to orographic lifting is also common at higher elevations. Even though mountain stations are colder and often wetter than locations at lower elevations, highland climates are often very similar to those in adjacent lowlands in terms of seasonal temperature cycles and precipitation distribution.

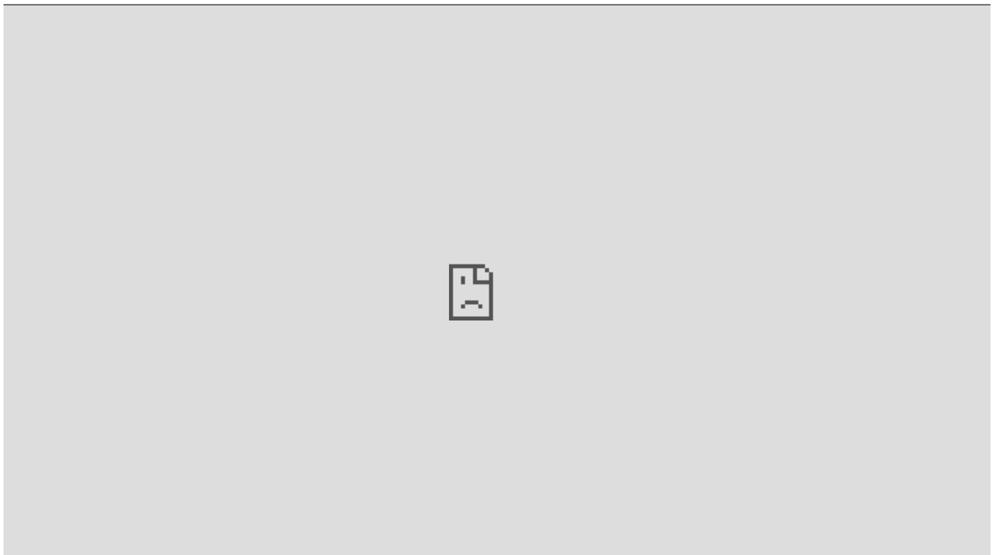
Phoenix, at an elevation of 338 meters (1109 feet), lies in the desert lowlands of southern Arizona. By contrast, Flagstaff is located at an altitude of 2134 meters (about 7000 feet) on the Colorado Plateau in northern Arizona (Figure 15.25). When summer average temperatures climb to 34°C (93°F) in Phoenix, Flagstaff experiences a pleasant 19°C (66°F), a full 15°C (27°F) cooler. Although the temperatures at the two cities are quite different, the annual march of temperature for both is similar, as they experience minimum and maximum monthly means in the same months. Precipitation data show similar seasonal patterns for both, but the amounts at Flagstaff are higher in every month. In addition, much of Flagstaff's winter precipitation is snow, whereas Phoenix gets only rain.

Smartfigure 15.25 **Highland climate**

This climograph, which includes data for two stations in Arizona, illustrates the general influence of elevation on climate. Flagstaff is cooler and wetter because it is nearly 1800 meters (6000 feet) higher than Phoenix.



Watch **SmartFigure: Highland Climates**



Eye on the Atmosphere 15.1

These images show an aerial view and close-up of a portion of the Trans-Alaska Pipeline. This structure extending 1300 kilometers (800 miles) was constructed in the 1970s to transport oil from Prudhoe Bay on Alaska's North Slope southward to the ice-free port of Valdez on the Gulf of Alaska. Because temperatures in this region range from cool to frigid, the oil must be heated to flow properly. Pumping stations along the way keep the oil moving through the pipeline.

Apply What You Know

1. The pipeline passes through subarctic (Dfc) and tundra (ET) climate zones. In which climate zone were these photos taken? What clue in the photos helped you figure this out?
2. Notice that in these views, the pipeline is suspended above ground. Based on your knowledge of the climate and landscape of the region, suggest a reason why the pipeline is elevated.

Because topographic variations are pronounced in mountains, every change in slope with respect to the Sun's rays produces a different *microclimate*. In the Northern Hemisphere, south-facing slopes are warmer and drier because they receive more direct sunlight than do north-facing slopes and deep valleys. Wind direction and speed in mountains can be highly variable and quite different from the movement of air aloft or over adjacent plains. Mountains create various obstacles to winds. Locally, winds may be funneled through valleys or forced over ridges and around mountain peaks. When weather conditions are fair, mountain and valley breezes are created by the topography itself.

We know that climate strongly influences vegetation, which is the basis for the Köppen system. Thus, where there are vertical changes in climate, we should expect a vertical zonation of vegetation as well. Ascending a mountain provides views of dramatic vegetation changes that otherwise might require a poleward journey of thousands of kilometers. This occurs because altitude duplicates, in some respects, the influence of latitude on temperature and hence on vegetation types. However, we know that other factors—such as slope orientation, exposure, winds, and orographic effects—also play roles in controlling the climate of highlands. Consequently, although the concept of vertical life zones applies on a broad regional scale, the details within an area vary considerably. Some of the most obvious variations result from differences in rainfall or the receipt of solar radiation on opposite sides of a mountain.

To summarize, *variety* and *changeability* best describe highland climates. Because atmospheric conditions fluctuate with altitude and exposure, a nearly limitless variety of local climates occurs in mountainous regions. Dramatic differences are observed in protected valleys compared to those on exposed peaks, windward slopes contrast sharply with those on the leeward sides, and slopes facing the Sun are unlike those that lie mainly in the shadows.

Concept Checks 15.7

- Briefly describe the highland climate (H).
- Arizona cities Flagstaff and Phoenix are relatively close to one another yet have contrasting climates. In what ways do they differ, and why?

Concepts in Review

15.1 Climate Classification and Controls

LO 1 Describe the criteria used in the Köppen system of climate classification. List and briefly discuss the major controls of climate.

Key Terms

Köppen classification system

marine climate

continental climate

- The most important elements in climate descriptions are temperature and precipitation because they have the greatest influence on people and the environment.
- An early attempt at climate classification by the Greeks divided each hemisphere into three zones: torrid, temperate, and frigid.
- The Köppen classification classifies climate according to dominant vegetation types and uses mean monthly and annual values of temperature and precipitation.
- The global distribution and characteristics of climate types reflects the major climate controls: latitude, land and water, geographic position and prevailing winds, mountains and highlands, ocean currents, and pressure and wind systems.

15.2 Humid Tropical Climates (A)

LO 2 Distinguish among the three categories of humid tropical climates.

Key Terms

tropical wet climate (Af)

tropical rain forest

intertropical convergence zone (ITCZ)

tropical wet and dry climate (Aw)

savanna

tropical monsoon climate (Am)

monsoon

- Straddling the equator, the tropical wet climate (Af) exhibits constant high temperatures and year-round rainfall that combine to produce the most luxuriant vegetation in any climatic realm—the tropical rain forest. Temperatures in these regions usually average 27°C (80°F) or more each month.
- Precipitation in Af climates usually exceeds 200 centimeters (80 inches) per year. Thermally induced convection associated with the equatorial low, coupled with convergence along the intertropical convergence zone (ITCZ), leads to ascent of the warm, humid, unstable air—ideal conditions for cloud formation and precipitation.
- The tropical wet and dry (Aw) climate region is a transitional zone between the rainy tropics and the subtropical steppes and is characterized by savanna, a tropical grassland with scattered deciduous trees. Precipitation in Aw regions is seasonal—wet summers followed by dry winters.
- The tropical monsoon climate (Am) is dominated by alternating periods of rainfall and drought that are associated with the monsoon —wind systems with a pronounced seasonal reversal of direction. The

tropical monsoon climate is found mainly on the windward coasts of landmasses, particularly in tropical Southeast Asia.

15.3 The Dry Climates (B)

LO 3 Contrast low-latitude dry climates and middle-latitude dry climates.

Key Terms

desert (arid, BW)

steppe (semiarid, BS)

subtropical desert (BWh)

subtropical steppe (BSh)

midlatitude desert (BWk)

midlatitude steppe (BSk)

- Dry regions of the world cover about 30 percent of Earth's land area. Climatologists define a dry climate as one in which the yearly precipitation is less than the potential water loss by evaporation. The two climates defined by a general water deficiency are arid, or desert (BW), and semiarid, or steppe (BS).
- Dominated by subtropical highs, the subtropical desert (BWh) and subtropical steppe (BSh) climates lie near the Tropic of Cancer and the Tropic of Capricorn. Within subtropical deserts, the scant precipitation is both infrequent and erratic.
- Owing to cloudless skies and low humidity, low-latitude deserts in the interiors of continents have the greatest daily temperature ranges on Earth. Where subtropical deserts are found along the west coasts of continents, cold ocean currents produce cool, humid conditions, often shrouded by low clouds or fog.
- Unlike their low-latitude counterparts, middle-latitude deserts (BWk) and middle-latitude steppes (BSk) exist principally because of their position in the deep interiors of of large landmasses.


Witold Skrypczak/Getty Images

15.4 Mild Midlatitude Climates (C)

LO 4 Distinguish among the three categories of C climates.

Key Terms

humid subtropical climate (Cfa)

marine west coast climate (Cfb)

mediterranean climates (Csa, Csb)

- The average temperature of the coldest month in mild midlatitude climates (C climates) is less than 18°C (64°F) but above −3°C (27°F).
- Humid subtropical climates (Cfa) are on the eastern sides of the continents, in the 25° to 40° latitude range.
- In North America, the marine west coast climate (Cfb) extends from near the U.S.–Canadian border northward as a narrow belt into southern Alaska. The prevalence of maritime air masses means mild winters, cool summers, and ample rainfall throughout the year.
- Mediterranean climates (Csa and Csb) are typically found along the west sides of continents, between latitudes 30° and 45°. In summer, the regions are dominated by stable oceanic subtropical highs, while in winter they experience frequent cyclonic storms, resulting in a wet season.

15.5 Midlatitude Climates with Severe Winters (D)

LO 5 Summarize the characteristics of the two categories of D climates.

Key Terms

humid continental climate (Dfa)

subarctic climates (Dfc, Dfd)

taiga climate

- The average temperature of the coldest month in midlatitude climates with severe winters (D climates) is −3°C (27°F) or below, and the average temperature of the warmest month exceeds 10°C (50°F).
- Humid continental climates (Dfa) are land controlled and are confined to central and eastern North America and Eurasia, in the latitude range 40° to 50°N. Both winter and summer temperatures in Dfa climates can be characterized as severe—cold winters and hot summers.
- Subarctic climates (Dfc and Dfd), often called taiga climates because they correspond to the coniferous forests of the same name, are situated north of the humid continental climates. The outstanding feature of subarctic climates is the dominance of winter.

15.6 Polar Climates (E)

LO 6 Contrast tundra and ice cap climates.

Key Terms

tundra climate (ET)

tundra

permafrost

ice-cap climate (EF)

- Polar climates (ET and EF) are those in which the mean temperature of the warmest month is below 10°C (50°F). Polar climates have the lowest annual mean temperatures on Earth.
- Two types of polar climates are recognized. The tundra climate (ET), marked by the 10°C (50°F) summer isotherm at its equatorward limit, is a treeless region of grasses, mosses, and lichens with permanently frozen subsoil, called permafrost.
- The ice-cap climate (EF) does not have a single monthly mean above 0°C (32°F), prohibiting the growth of vegetation, and the landscape is one of permanent ice and snow.

15.7 Highland Climates (H)

LO 7 List the characteristics of highland climates.

- Highland climates are characterized by a great diversity of climatic conditions across small areas. Although the best-known climatic effect of increased altitude is lower temperatures, greater precipitation due to orographic lifting is also common.
- Variety and changeability best describe highland climates.

Exercises and Online Activities

Mastering Meteorology™

For instructor-assigned homework, test prep resources, and other learning materials, visit **Mastering Meteorology.**

Review Questions

1. Why are temperature and precipitation used to classify climates? Contrast marine and continental climates.
2. Explain the connection between pressure systems and the global distribution of precipitation.
3. What characterizes the humid tropical climates?
4. Describe the tropical wet climate.
5. Define *monsoon*.
6. Explain why the amount of precipitation alone can't be used to define the humid–dry boundary.
7. Why do daytime ground and air temperatures reach such high values in the subtropical desert climate (BWh)?
8. What is the difference between a desert and a steppe?
9. Describe the general location of midlatitude deserts (BWk) and how they are different from subtropical deserts (BWh).
10. Describe the general location, temperature, and precipitation characteristics of the humid subtropical climates (Cfa). Do the same for mediterranean climates (Csa, Csb).
11. What causes the relatively mild temperatures of the marine west coast climate?
12. Compare and contrast the humid continental climate (Dfa) and the subarctic climate (Dfc).
13. What temperature characteristic distinguishes tundra climate (ET) from ice-cap climate (EF)?
14. Why do polar regions remain cool in summer, despite extended periods of daylight?
15. Describe how highlands affect annual precipitation.

Give It Some Thought

1. In which of the following climates is annual rainfall likely to be most consistent—that is, which would probably experience the smallest *percentage change* in rainfall from year to year: BSh, Aw, BWh, or Af? In which of these climates is the annual rainfall most *variable* from year to year? Explain your answers.
2. Identify three deserts visible on this classic view of Earth from space. Briefly explain why these regions are so dry. Identify two other prominent climates in this image. In addition, explain the cause of the band of clouds in the region of the equator.


NASA

3. Albuquerque, New Mexico, which receives an average of 20.7 centimeters (8.07 inches) of rainfall annually, is considered a desert in the Köppen classification. The Russian city of Verkhoyansk is located near the Arctic Circle in Siberia. The yearly precipitation at Verkhoyansk averages 15.5 centimeters (6.05 inches), about 5 centimeters (2 inches) less than Albuquerque, yet it is classified as a humid climate. Explain why they are classified differently.
4. This problem examines two places in North Africa adjacent to the Sahara Desert, and both are classified as subtropical steppe (BSh)

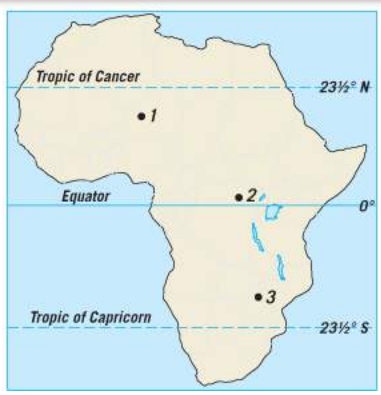
climate. One place is on the southern margin of the Sahara, and the other is north of the Sahara near the Mediterranean Sea.

a. In which season, summer or winter, does each place receive its maximum precipitation? Explain.

b. If both stations barely meet the requirements for steppe climates (that is, with only a little more rainfall, both would be considered humid), which station would probably have the lower rainfall total? Explain.

5. Refer to the monthly rainfall data (in millimeters) for three cities in Africa shown on the accompanying map. Match the data for each city (A, B, or C) to the correct location (1, 2, or 3) on the map. How were you able to figure this out? *Bonus:* Select a figure in Chapter 7 that would be especially useful in explaining or illustrating why these places have rainfall maximums and minimums when they do.

	J	F	M	A	M	J	J	A	S	O	N	D
City A	81	102	155	140	133	119	99	109	206	213	196	122
City B	0	2	0	0	1	15	88	249	163	49	5	6
City C	236	168	86	46	13	8	0	3	8	38	94	201



6. Refer to Figure 15.3, which shows climates of the world. Humid continental (Dfb and Dwb) and subarctic (Dfc) climates are usually described as being “land controlled”—that is, they lack marine influence. Nevertheless, these climates are found along the margins of the North Atlantic and North Pacific oceans. Explain why this occurs.

By the Numbers

1. Use Figure 15.2 to determine the appropriate classification for stations A, B, and C in the table below.

	J	F	M	A	M	J	J	A	S	O	N	D	YR
Station A													
Temp. (°C)	−18.7	−18.1	−16.7	−11.7	−5.0	0.6	5.3	5.8	1.4	−4.2	−12.3	−15.8	−7.5
Precip. (mm)	8	8	8	8	15	20	36	43	43	33	13	12	247
Station B													
Temp. (°C)	24.6	24.9	25.0	24.9	25.0	24.2	23.7	23.8	23.9	24.2	24.2	24.7	24.4
Precip. (mm)	81	102	155	140	133	119	99	109	206	213	196	122	1675
Station C													
Temp. (°C)	12.8	13.9	15.0	16.1	17.2	18.8	19.4	22.2	21.1	18.8	16.1	13.9	15.9
Precip. (mm)	53	56	41	20	5	0	0	2	5	13	23	51	269

2. Using the maps in Figure 15.19, determine the approximate January and July temperature gradients between the southern tip of mainland Florida and the point where the Minnesota–North Dakota border touches Canada. Assume the distance to be 3100 kilometers (1900 miles). Express your answers in °C per 100 kilometers or °F per 100 miles.

Beyond the Textbook

How Climate Change Might Affect Climate Classification

This activity illustrates how climate change could potentially affect the boundaries between the world's climate groups.

1. Current Climate Regions

Go to http://koeppen-geiger.vu-wien.ac.at/shifts.htm, which provides Köppen-Geiger climate classification maps. Below the two maps find the download link, and download the Observed: 1976–2000 climate map. Zoom in on North America to answer the following.

1. What is the climate classification code for the interior of Greenland?
2. Use your textbook and the climate code to identify the climate for the interior of Greenland, and briefly describe this climate type.
3. What is the climate classification code for southernmost Florida?
4. Use your textbook to identify the climate for this part of Florida, and briefly describe this climate type.
5. Repeat Steps 1 and 2 for your approximate location.

2. Future Climate Regions

Using a separate window, open the website listed above, and download the A1FI: 2076–2100 map (the link is just below the one you clicked for the above questions). This A1FI map shows a climate change scenario that includes rapid economic growth and intense use of fossil fuels. Zoom in to North America and compare this map with the 1976–2000 climate map.

1. Describe how the climate is projected to change in Greenland by the latter part of this century.
2. If this scenario is correct, what impact would the change in Greenland's climate likely have on locations around the world? (Do an Internet search on this topic, if needed.)
3. Describe how the climate in southern Florida is projected to change.
4. What is the Köppen-Geiger climate classification in your approximate location according to the 2076–2100 map? Describe the projected climate change, if any.
5. In what direction (north or south) are climate zones predicted to shift in the Eastern United States?
6. How is the climate in the Great Lakes region predicted to change?

Chapter 16 Optical Phenomena of the Atmosphere

Rainbows are among the most common and spectacular of the atmosphere's optical phenomena.

Focus on Concepts

Each statement represents the primary learning objective for the corresponding major heading within the chapter. After you complete the chapter, you should be able to:

1. Explain the principle called the *law of reflection* and discuss how refraction causes white light to separate into the spectrum of colors (16.1).
2. Describe how inferior and superior mirages form (16.2).
3. Sketch a raindrop and show how sunlight travels through it to form a primary rainbow (16.3).
4. Distinguish among three different optical phenomena that are produced as a result of the interaction between sunlight and hexagonal ice crystals (16.4).
5. Compare and contrast coronas and halos (16.5).

One of Earth's most spectacular and intriguing natural phenomena is the rainbow. Its "surprise" appearance and splash of colors make it the subject of both poets and artists, not to mention nearly every casual photographer within reach of a camera. In addition to rainbows, many other stunning optical phenomena occur in our atmosphere. In this chapter, we consider how the most familiar of these displays occur. Knowing when and where to look for these phenomena will allow you to identify each type and, ultimately, observe and appreciate them more frequently.

16.1 Interactions of Light and Matter

LO 1 Explain the principle called the *law of reflection* and discuss how refraction causes white light to separate into the spectrum of colors.

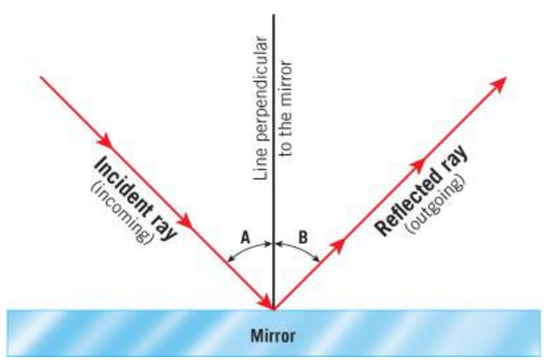
The interaction of visible sunlight with our atmosphere creates the numerous optical phenomena we observe in the sky. In Chapter 2 we considered some properties of light and how they contribute to occurrences such as the blue color of the sky and the red color of sunset. This chapter examines other interactions between sunlight and the gases, ice crystals, and water droplets found in the atmosphere that generate still other optical phenomena. We begin with two fundamental ways light and matter interact: *reflection* and *refraction*.

Reflection

Light coming from the Sun toward Earth travels at a uniform speed and in a straight line. However, when light encounters a transparent material, such as a water body, a portion bounces off the surface, and some is transmitted through the material at a slower velocity. The light that bounces back from the surface is *reflected*. Reflected light allows you to see yourself in a mirror. The image that you see in a mirror originates as light that first reflected off you toward the mirror and then was bounced from the mirror back to your eyes. When light is reflected, the rays bounce off the reflecting surface at the same angle at which they met that surface (Figure 16.1). This principle is called the **law of reflection**. It states that the angle that the incident (incoming) ray makes with a line perpendicular to the reflective surface is equal to the angle that the reflected (outgoing) ray makes to that same line.

Figure 16.1 Reflection of light by a mirror

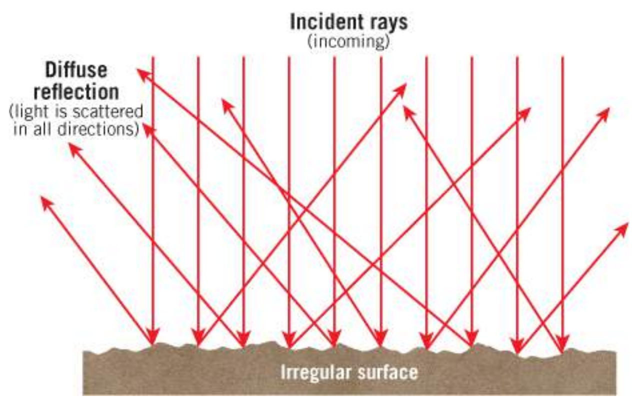
When light rays are reflected from a smooth surface, they bounce off the surface at the same angle at which they met the surface.



> The law of reflection states that the angle of incidence equals the angle of reflection.

On a smooth, highly reflective surface such as a mirror, about 90 percent of the parallel incoming rays leave the surface by following outgoing parallel paths. However, when light encounters a slightly irregular surface, the rays are reflected in many directions; this is referred to as *diffuse reflection* (Figure 16.2). Even something that appears as smooth as a page in this book is sufficiently rough to scatter light in all directions. This type of reflection makes it possible to read the print from almost any angle. Most of the objects in our surroundings are seen by diffuse reflection.

Figure 16.2 Sunlight striking a rough surface is scattered



When light is reflected from a very rough surface, the image you see is generally distorted or may appear as multiple images. For example, the reflected image of the Sun when viewed on a wavy ocean surface is not a circular disk but a long, narrow band, as shown in Figure 16.3. What you see is not one image of the Sun but many distorted images of a single light source. This bright band of light is produced because only a portion of the sunlight that strikes each wave is reflected toward the viewer's eyes.

Figure 16.3 Reflected image of the Sun viewed on a wavy ocean surface

This long, narrow band of sunlight is really multiple distorted images of the Sun reflected from the water surface.

Another type of reflection that is important to our discussion of optical phenomena is called **internal reflection**. Internal reflection occurs when light that travels through a transparent material, such as water, reaches the opposite surface and is reflected back into the same transparent material. You can easily demonstrate this phenomenon by holding a glass of water directly overhead and looking up through the water. You should be able to see clearly through the water because very little internal reflection results when light strikes perpendicular to the surface of a transparent material. While keeping the glass overhead, move it sideways so that you look through the glass at an angle. The underside of the surface of the water takes on the appearance of a silvered mirror. What you are observing is the internal reflection that occurs when light strikes a water surface at an angle greater than 48° from the vertical (Figure 16.4). Internal reflection plays an important role in the formation of optical phenomena such as rainbows.

Figure 16.4 Internal reflection

Notice the reflection that appears above the two girls swimming in a pool. Internal reflections are caused by light that is reflected off the interface between the water's surface and the air above.

Refraction

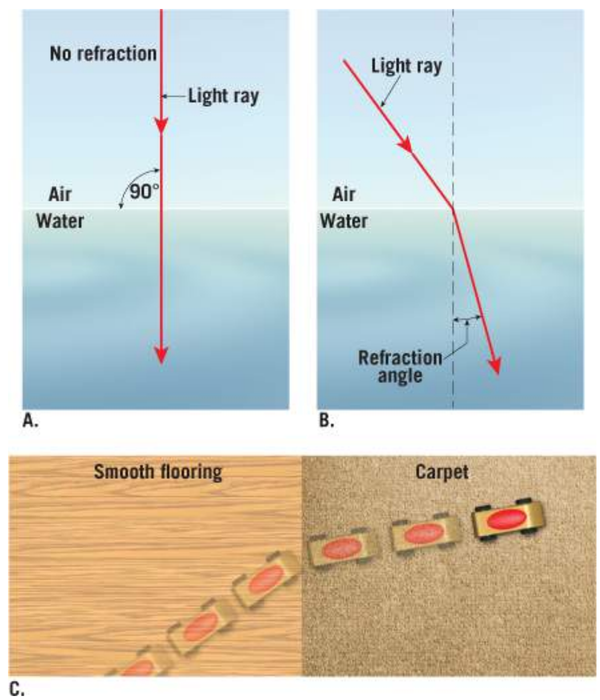
When light strikes a transparent material, the portion that is not reflected is transmitted through the material and undergoes another well-known effect, called *refraction*. **Refraction** is the change of direction of light as it passes obliquely from one transparent medium to another. Refraction occurs because the velocity of light depends on the material through which it is transmitted. In a vacuum, radiation travels at the speed of light (3.0×10^8 meters per second), but when it travels through air, its speed is slowed slightly. However, in transparent substances such as water, ice, or glass, its transmission speed is considerably slower than in air.

> Refraction occurs when light bends as it passes from one medium to another.

When light encounters a transparent medium, such as water, at a 90° angle, it travels though that medium in a straight path, as shown in Figure 16.5A. However, when light encounters a transparent medium at an angle of less than 90°, it bends, or refracts (Figure 16.5B). Refraction can be demonstrated by seeing how a toy car responds when it rolls from smooth flooring onto a carpeted surface. If the toy car meets the carpet at a 90° angle, it slows down but does not change direction. However, if the front wheels of the car hit the carpet at an angle other than 90°, the car not only slows but also changes direction, as shown in Figure 16.5C. In this analogy, the directional change occurs because the front wheel that hit the carpet first begins to slow while the other front wheel, which is still on the smooth flooring, continues at the original speed, resulting in a sudden turn of the toy car. Now imagine that the path of the toy car represents the path of light rays and that the smooth flooring and carpet represent air and water, respectively. As light enters the water and is slowed, its path is diverted toward a line extending perpendicular to the water's surface (Figure 16.5B). If the light passes from water into air, the bending occurs in the opposite direction—away from the perpendicular.

Figure 16.5 Refraction

A. When light rays pass from one transparent material into another at an angle of 90°, the rays travel in a straight path. **B.** Light waves are refracted (bent) when they pass from one transparent material into another at an angle other than 90°. The speed of light is slower in water than in air, which causes light rays to bend toward a line drawn perpendicular to the water surface. **C.** A toy car traveling from a smooth surface to a carpeted floor behaves similar to light being refracted.

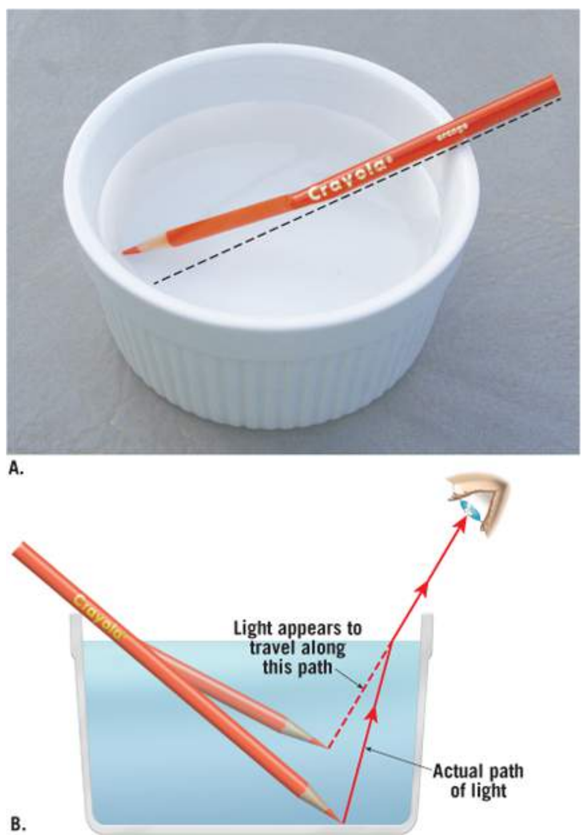


Refraction can be demonstrated by immersing a pencil halfway into a glass of water and viewing the pencil obliquely—an angle other than 90° to the surface (Figure 16.6A). How refraction produces the apparent bending of a pencil is illustrated in Figure 16.6B. The solid lines in this sketch show the actual path taken by the light, whereas the dashed lines indicate the straight path a human brain perceives. As we look down at the pencil, the point appears to be closer to the surface than it actually is.

This occurs because our brain perceives the light as coming along the straight path indicated by the dashed line, rather than along the actual bent path. Because all the light coming from the submerged portion of the pencil is bent similarly, this portion of the pencil appears nearer the surface. Therefore, where the pencil enters the water, it appears to be bent upward, toward the surface.

Figure 16.6 Demonstration of refraction using a pencil

A. Image illustrating refraction of a pencil immersed in water. **B.** The pencil appears bent because the eye perceives light as if it were traveling along the dashed line rather than along the solid line, which represents the path of the refracted light.

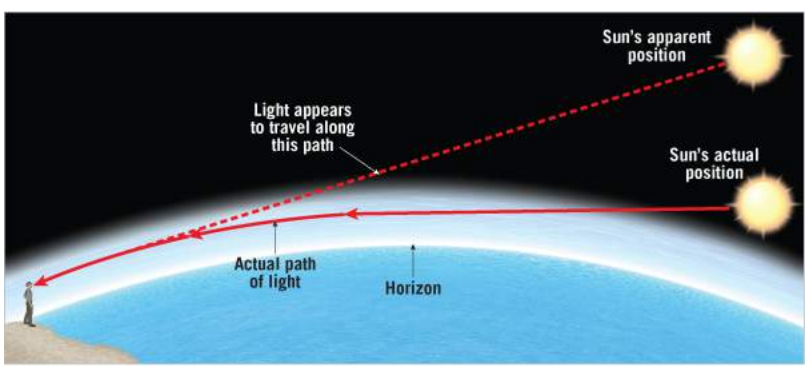


In addition to the abrupt bending of light as it passes obliquely from one transparent substance to another, light also gradually bends as it traverses a material of varying density. As the density of a material changes, the velocity of light changes as well. Within Earth's atmosphere, for example, the density of air usually increases toward Earth's surface. The result of this gradual density change is an equally gradual slowing and bending of light rays. Rays that travel from areas of lower air density to areas of higher air density curve in a direction that has the same orientation as Earth's curvature.

The bending of light caused by refraction is responsible for a number of common optical phenomena. These phenomena result because our brain perceives bent light as if it has traveled to our eyes along a straight path. One example is how we view the setting Sun. Several minutes after the Sun has actually slipped below the horizon, it still appears to us as a full disk. Figure 16.7 illustrates this situation. It is our *inability to perceive light bending* that causes the position of the Sun to appear above the horizon after it has set.

Figure 16.7 **Refraction causes an apparent displacement of the position of the Sun**

This displacement is the result of sunlight being refracted as it passes through layers of the atmosphere that have different densities. Because the atmosphere is less dense aloft than it is at the surface, it causes light to bend with the same curvature as Earth's surface.



Concept Checks 16.1

■ Briefly describe the optical phenomenon known as *internal reflection*.

■ What happens to light as it passes obliquely from one transparent medium into another?

■ Provide at least one example of how *refraction* changes the way we perceive an object.

16.2 Mirages

LO 2 Describe how inferior and superior mirages form.

One of the most interesting optical events common to our atmosphere is the **mirage**. Although this phenomenon is most often associated with desert regions, it can be experienced anywhere (Box 16.1). Mirages fall into two major categories, *inferior* and *superior*, based on the mirage's apparent position relative to the position of the object that produces the mirage.

Box 16.1

Are Highway Mirages Real?

You have undoubtedly seen a mirage while traveling along a highway on a hot summer afternoon. The most common highway mirages are in the form of “wet areas” that appear on the pavement ahead, only to disappear as you approach (Figure 16.A). Because the “water” always disappears as a person gets closer, many people believe these mirages are only optical illusions. This is not the case. Highway mirages, as well as all other types of mirages, are as real as the images observed in a mirror. As shown in Figure 16.A, highway mirages can be photographed and therefore are not tricks played by the mind.

Figure 16.A A classic highway mirage

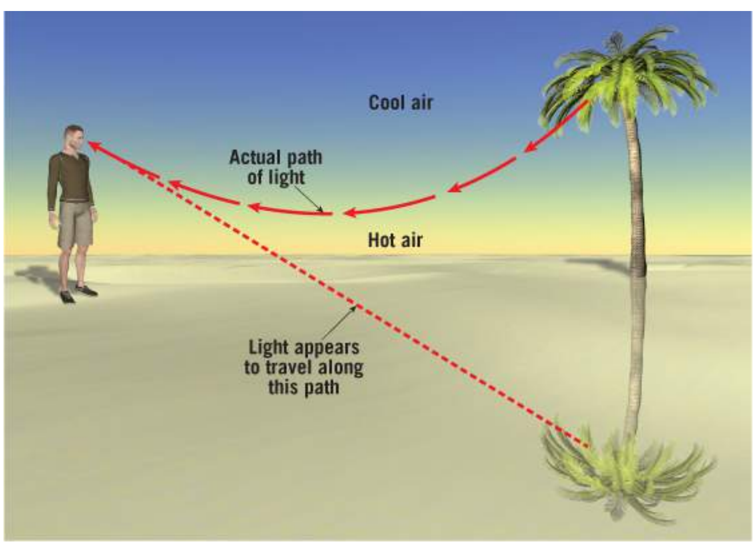
What causes the “wet areas” that appear on dry pavement? On hot summer days, the layer of air near Earth’s surface is much warmer than the air aloft. Sunlight traveling from a region of colder (denser) air into the warmer (less dense) air near the surface bends in a direction opposite to Earth’s curvature (see Figure 16.8). Consequently, light rays that began traveling downward from the sky are refracted upward and appear to the observer to have originated on the pavement ahead. What looks like water on the highway is really just an inverted image of the sky. This can be verified by careful observation. The next time you view a highway mirage, look closely at any vehicle ahead of you at about the same distance as the “wet” area. Below the vehicle, you should be able to see an inverted image of it. Such an image is produced in the same manner as the inverted image of the sky.

Apply What You Know

1. Explain the cause of the “wet areas” that sometimes appear in the distance when you are driving on a hot, clear summer day.

Figure 16.8 **The classic desert mirage is a type of inferior mirage**

In the classic desert mirage, light travels more rapidly in the hot air near Earth’s surface than in the cooler air above. Thus, as downward-directed light rays enter the warm air near the surface, they are bent (refracted) upward so that they reach the observer from below eye level, causing objects to appear lower than they actually are.



Inferior mirages are observed on very hot days, when the air near the ground is much hotter and, therefore, much less dense than the air aloft.

As noted earlier, a change in the density of air is accompanied by a gradual bending of the light rays. When sunlight travels through air that is less dense near the surface, the rays bend upwards as shown in Figure 16.8. This direction of bending causes the light from a distant object to approach the observer from below eye level. Because the brain perceives the light as following a straight path, the object appears below its original position and is *inverted*, as illustrated with the palm tree in Figure 16.8. The palm tree appears upside down because the rays that originate near the top of the tree are bent more than those originating near the base of the tree.

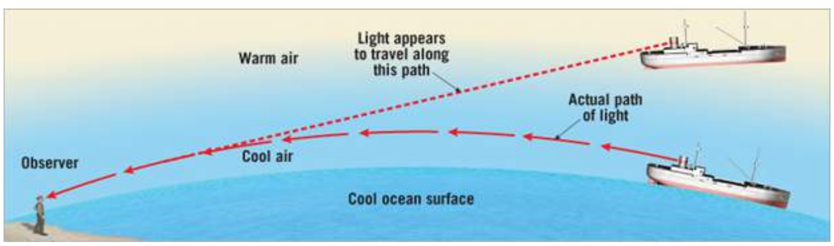
> Light traveling through air of different densities is refracted, which can produce a mirage.

In the classic inferior mirage, called the *desert mirage*, a lost and thirsty wanderer encounters an image consisting of an oasis of palm trees and a shimmering water surface on which a reflection of the palms is "seen." Although the palm trees are real, the water and refracted image of the palms are part of the mirage. Light traveling to the observer through the cooler air above produces the image of the actual trees. The reflected image of the palms is produced from light that traveled downward from the trees and was gradually bent upward as it traveled through the hot (less dense) air near the ground. The image of shimmering water is produced by light that travels downward from the sky and is bent upward. Thus, the water mirage is actually the sky. These desert mirages are called *inferior mirages* because the images appear *below* the true location of the observed object.

A **superior mirage** forms when the air near the ground is much cooler and, therefore, denser than the air aloft. Consequently, this effect is observed most frequently in polar regions or over cool ocean surfaces. When air near the ground is substantially colder than the air above, light bends downward. As shown in Figure 16.9, this effect allows ships to be seen where Earth's curvature would block them from view. This type of superior mirage, called *looming*, occurs when the bending of light is significant enough to make the object appear suspended above the horizon. In contrast to a desert mirage, which is an inferior mirage, looming is a superior mirage because the image is seen *above* its true position.

Figure 16.9 Looming: A type of superior mirage

When light enters a layer of cool air near the surface, it slows and bends downward. This causes objects to be seen above their actual position, hence the term *superior mirage*.



> An object appears *below* its true position in an inferior mirage, but *above* its position in a superior mirage.

In addition to looming, several variations of the superior mirage are spectacular sights and have been separately identified. They occur when the atmosphere develops a temperature profile in which the temperature changes erratically with altitude, causing irregular changes in the air's density. Under these conditions, each thermal layer acts like a glass magnifying lens. Because each layer bends light rays somewhat differently, the size and shape of the objects observed through these thermal layers can be greatly distorted. In addition, these erratic changes in air density can produce superior mirages that appear inverted or upright.

One type of superior mirage, called *towering*, results in an apparent change in size of an object. As the name implies, towering creates a much taller, and often distorted, image of the original object. Towering is most frequently observed in coastal areas, where sharp temperature contrasts are common. An interesting type of towering is called the *Fata Morgana*, named for the legendary sister of King Arthur, who was credited with the magical power of being able to create towering castles out of thin air (Figure 16.10). In addition to generating magical castles, the Fata Morgana explains the towering mountains that early explorers of the polar regions of the globe observed in the distance but never materialized.

Figure 16.10 **Fata Morgana**

This type of mirage makes objects look taller than they actually are. This particular image is of two icebergs floating on water. Notice that the upper portion of this image (the mirage) is an inverted image of the actual iceberg.

Eye on the Atmosphere 16.1

The accompanying image is an optical phenomenon known as a *green flash* that appears as a green cap above the Sun at sunset or sunrise. Green flashes result from atmospheric changes in density that cause sunlight to bend as it travels from the thinner air in the upper atmosphere into the denser air near Earth’s surface, where the observer is located. Green flashes are produced because the light at the blue/green end of the spectrum is bent more than the light in the red/orange range. As a result, the blue rays from the upper limb of the setting Sun remain visible to an observer on Earth after the red rays are obstructed by Earth’s curvature. We should, therefore, expect to see a glimpse of blue/green light at each sunset. Clear conditions and an unobstructed view of the sunset produce the most vivid emerald green flashes. However, because almost all the blue light and much of the green light is removed from a sunbeam by scattering (see Chapter 2), green flashes are rarely observed.

Apply What You Know

1. What term is used for the bending of light as it travels through a transparent material that exhibits various densities?
2. Green flashes are most commonly photographed over the ocean at sunset. Suggest a reason for this.

You might have wondered . . .

Why is the Moon much larger when it is low on the horizon than when it is overhead?

This phenomenon is an optical illusion that has nothing to do with the refraction of light. The size of the Moon does not actually change as it rises above the horizon. As meteorologist Craig Bohren stated, "The Moon illusion results from refraction by the mind, mirages from refraction by the atmosphere."*

* Craig F. Bohren, *What Light Through Yonder Window Breaks?: More Experiments in Atmospheric Physics* (New York: John Wiley & Sons, Inc), ©1991.

Concept Checks 16.2

- Explain what happens to light if the density of the air through which it travels changes with height.
- When light travels from warm (less dense) air into a region of colder (denser) air, its path will curve. Does it bend in the same direction as Earth's curvature or in the opposite direction?
- How is an inferior mirage different from a superior mirage?

16.3 Rainbows

LO 3 Sketch a raindrop and show how sunlight travels through it to form a primary rainbow.

Probably the best known and most spectacular of all optical phenomena in our atmosphere is the **rainbow** (Figure 16.11). An observer on the ground sees a rainbow as an arch-shaped array of colors that spans a large segment of the sky. Although the clarity of the colors varies with each rainbow, an observer can usually discern six rather distinct bands of color. The outermost band is red and blends gradually to orange, yellow, green, blue, and eventually violet light. These spectacular splashes of color are seen when the Sun is behind the observer and a rain shower is in front. A fine mist of water droplets generated by a waterfall or lawn sprinkler can also generate miniature rainbows.

Figure 16.11 Rainbow

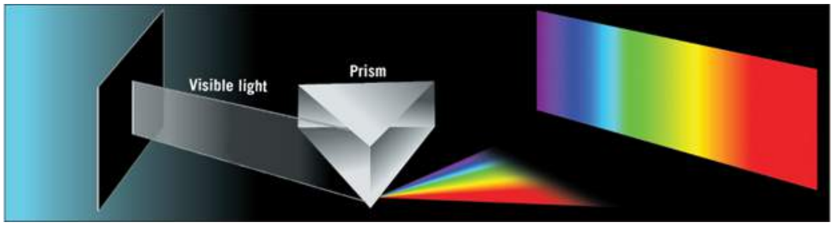
This rainbow appears over spruce trees in the taiga (boreal forest) north of the Alaska Range.

> To see a rainbow, you must be facing the rain with the sun at your back.

Seventeenth-century scientist Sir Isaac Newton used a prism to demonstrate the separation of light into colors to form a rainbow. Light transmitted through a prism is refracted twice—once as it passes from the air into the glass and again as it leaves the prism and reenters the air. Newton noted that when light is refracted twice, as by a prism, the separation of sunlight into its component colors is quite noticeable (Figure 16.12). We refer to this separation of colors by refraction as **dispersion**.

Figure 16.12 The spectrum of colors is produced when sunlight passes through a prism

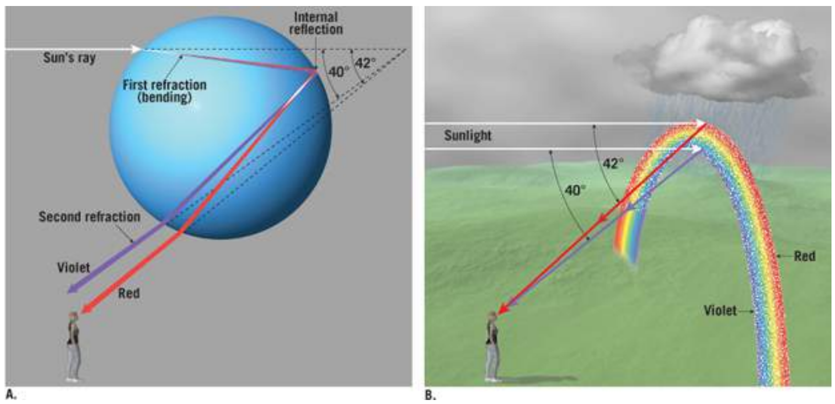
Notice that each wavelength (color) of light is refracted (bent) differently.



Rainbows are generated because water droplets act like prisms, dispersing sunlight, which contains all colors, into the spectrum of separate colors. Upon entering a droplet, the sunlight is refracted, with violet light bent the most and red the least (Figure 16.13A). Then, when the sunlight reaches the opposite side of the droplet, the rays are internally reflected backward and exit the droplet on the same side they entered. As they leave the droplet, further refraction increases the amount of dispersion and accounts for the nearly complete color separation.

Figure 16.13 **The formation of a primary rainbow**

A. Color separation results when sunlight is refracted as it enters a raindrop. This light is then internally reflected, and it is refracted again when it leaves the raindrop, resulting in the colors of the rainbow. **B.** It takes millions of raindrops to produce a rainbow. Each observer sees only one color from any one raindrop.



> Rainbows form when light gets refracted, internally reflected, and then refracted again as it travels through a raindrop.

The angle between the incoming (incident) rays and the dispersed colors that constitute the rainbow is 40° for violet and 42° for red light. The other colors—orange, yellow, green, and blue—are dispersed at angles between 40° and 42°. Although each droplet disperses the full spectrum of colors, an observer sees only one color from any single raindrop. For example, if red light from a particular droplet reaches an observer's eye, the violet light from that droplet is visible only to an observer in a different location (Figure 16.13A). Consequently, each observer sees his or her "own" rainbow, which is generated by a different set of droplets and different rays of light. In effect, a rainbow is produced through the interaction of sunlight with millions of raindrops, each of which acts as a miniature prism.

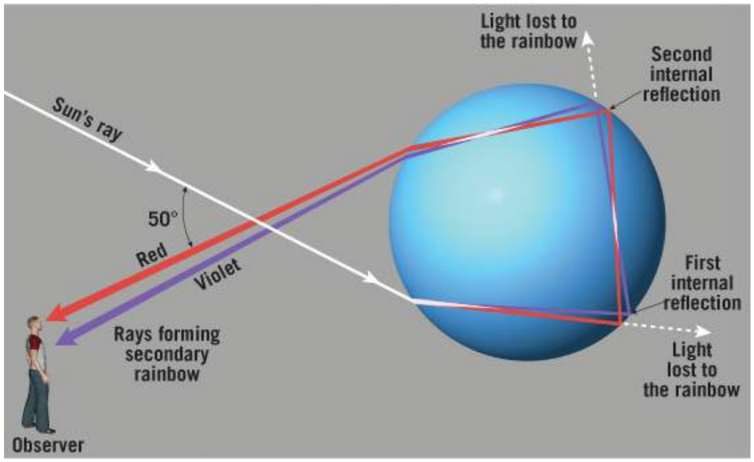
The curved shape of the rainbow results because the rainbow rays always travel toward the observer at an angle of about 42° from the path of the sunlight (Figure 16.13B). Thus, we experience a 42° semicircle of color across the sky that we identify as the arch shape of the rainbow. If the Sun is higher than 42° above the horizon, an observer on Earth will not see a rainbow. Under certain conditions, an observer in an airplane will see the rainbow as a full circle.

When a spectacular rainbow is visible, an observer will sometimes see a dimmer secondary rainbow. The secondary bow will be visible about 8° above the primary bow and will suspend a larger arc across the sky.* The secondary bow also has a slightly narrower band of colors than the primary rainbow, and the colors are in reverse order. Red makes up the innermost band of the secondary rainbow and violet the outermost.

The secondary rainbow is generated in much the same way as the primary bow. The main difference is that the dispersed light that constitutes the secondary bow is reflected twice within a raindrop before it exits, as shown in Figure 16.14. The extra internal reflection results in a 50° angle for the dispersion of the color red (about 8° greater than the primary rainbow) and a reverse order of the colors.

Figure 16.14 **Formation of a secondary rainbow**

A secondary rainbow consists of light rays that experienced two internal reflections rather than one. Notice that the double internal reflection causes the positions of the red and violet rays to be reversed, which accounts for the order of the colors.



The extra reflection also accounts for the fact that the secondary bow is less frequently observed than the primary bow (Figure 16.15). Each time light strikes the inner surface of the droplet, some of the light is transmitted through the reflecting surface. Because this light is "lost," it does not contribute to the brightness of the rainbow. Although secondary rainbows always form, they are rarely discernible.

Figure 16.15 Double rainbow

A secondary rainbow is dimmer than the primary bow, and the order of colors is reversed.

Humans use rainbows, like other optical phenomena, as a means of predicting the weather. A well-known weather proverb illustrates this point:

Rainbow in the morning gives you fair warning,

Rainbow in the afternoon, good weather coming soon.

This bit of weather lore relies on the fact that midlatitude weather systems usually move from west to east. Remember that observers must be positioned with their backs to the Sun and facing the rain in order to see a rainbow. When a rainbow is seen in the morning, the Sun is located to the east of the observer, and the clouds and raindrops that are responsible for its formation must therefore be located to the west. Thus, we predict the advance of foul weather when the rainbow is seen in the morning because the rain is located to the west and is traveling toward the observer. In the afternoon, the opposite situation exists: The rain clouds are located to the east of the observer. Therefore, when the rainbow is seen in the afternoon, the rain has already passed. Although this famous proverb has a scientific basis, a small break in the clouds that lets the sunshine through can generate a late-afternoon rainbow. In this situation, a rainbow may certainly be followed shortly by more rainfall.

Concept Checks 16.3

■ List the colors of a primary rainbow, in order, from the outer edge to the inner edge.

■ If you were looking for a rainbow in the morning, which direction would you look? Explain.

■ Why is a secondary rainbow less vibrant than a primary rainbow?

* For reference, when measuring how far apart objects are in the sky, hold your hand up to the sky. A pinky finger is roughly equal to 1°, three fingers is 5°, and stretched thumb to pinky is about 25°.

16.4 Halos, Sun Dogs, and Solar Pillars

LO 4 Distinguish among three different optical phenomena that are produced as a result of the interaction between sunlight and hexagonal ice crystals.

Although halos are a fairly common occurrence, they are rarely seen by casual observers. When noticed, a **halo** usually appears as a narrow whitish ring centered on the Sun or, less often, the Moon (Figure 16.16). Halos most often appear on days when the sky is covered with a thin layer of cirrus or cirrostratus clouds, (see Figure 5.2C, page 119). In addition, halos are seen most often in the morning or late afternoon, when the Sun is near the horizon. Residents of polar regions, where a low Sun and cirrus clouds are common, are frequently treated to views of halos and related phenomena.

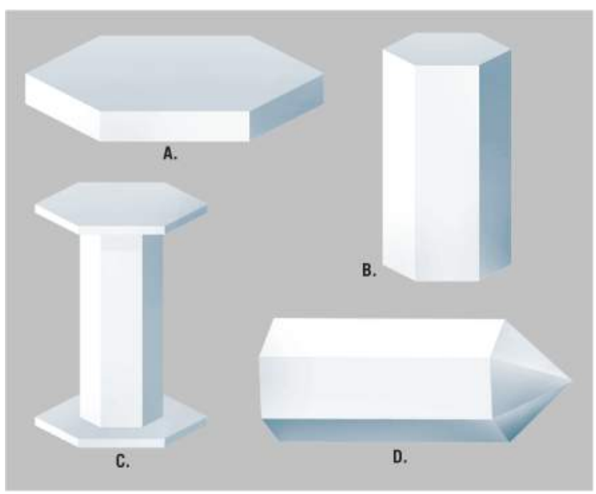
Figure 16.16 **A 22° halo produced by the dispersion of sunlight by ice crystals in cirrostratus clouds**

The most common halo is called the *22° halo*, named because it has a radius of 22°. Less frequently observed is the larger *46° halo*. Like a rainbow, a halo is produced by dispersion of sunlight. In the case of a halo, however, ice crystals rather than raindrops refract the light. Thus, the clouds most often associated with halo formation are high clouds. Because cirrus clouds often form as a result of frontal lifting, halos have been accurately described as harbingers of foul weather.

Four basic types of hexagonal (six-sided) ice crystals contribute to the formation of halos: plates, columns, capped columns, and bullets (Figure 16.17). Because the ice crystals responsible for halo formation typically have a random orientation, the diffused light produces a nearly circular halo centered on the illuminating object (Sun or Moon).

Figure 16.17 Some common ice crystal shapes found in high clouds

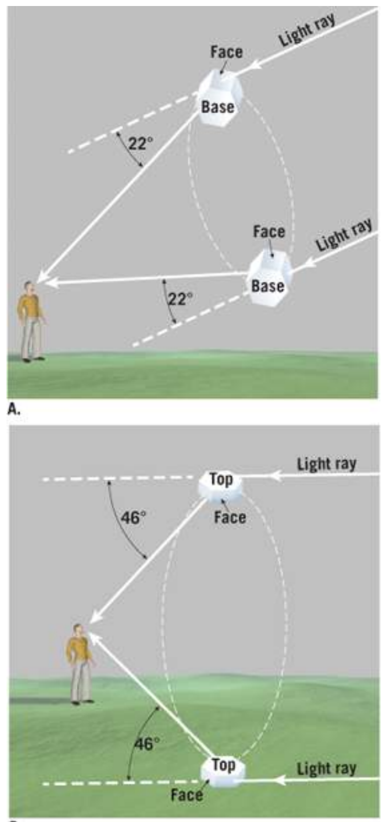
These particular hexagonal shapes contribute to the formation of certain optical phenomena: **A.** plate, **B.** column, **C.** capped column, and **D.** bullet.



The primary difference between 22° and 46° halos is the path that light takes through the ice crystals. The scattered sunlight responsible for the 22° halo enters one crystal face, is refracted, and then exits from a different face, as shown in Figure 16.18A. The angle of separation between the alternating faces of ice crystals is 60°, the same as in a common glass prism. Consequently, ice crystals disperse light in a manner similar to a prism to produce a 22° halo. A 46° halo, by contrast, is formed from light that passes through one face of the crystal, is refracted, and then exits either the top or base of the crystal (Figure 16.18B). The angle separating these two surfaces is 90°. Light that passes through ice crystal faces separated by a 90° angle is refracted so it is concentrated 46° from the light source, which accounts for its name. Many other types of halos and partial halos have been observed, all of which owe their formation to the relative abundance of ice crystals of particular shapes and orientations.

Figure 16.18 **Halos consist of light that is refracted as it passes through ice crystals**

A. A 22° halo is produced when the majority of sunlight or moonlight enters a face (rather than the base or top) of an ice crystal and exits one of the opposite faces. **B.** A 46° halo is generated when light enters one of the crystal faces and exits either the top or base of the ice crystal.



Although ice crystals disperse light in the same manner as raindrops (or prisms), halos are generally whitish and do not display the colors of the rainbow. This difference is primarily attributed to the fact that raindrops tend to be uniform in both size and shape, whereas ice crystals vary considerably in size and have imperfect shapes. Although individual ice crystals produce the rainbow of colors in a manner similar to raindrops, the colors tend to overlap and wash each other out. Occasionally, halos display some coloration; in such cases, a bluish ring surrounds a reddish ring.

> Halos and sun dogs are generated when light is refracted by ice crystals in cirrostratus clouds.

One of the most spectacular features associated with halos is **sun dogs**. These two bright regions, or "mock suns," as they are often called, can be seen adjacent to a 22° halo and on opposite sides of the Sun (Figure 16.19). Sun dogs form under the same conditions as, and in conjunction with, halos—except that their existence depends on the presence of numerous vertically oriented ice crystals. This particular orientation results when elongated ice crystals are slowly descending. Vertically oriented ice crystals cause the Sun's rays to be concentrated (much as with a magnifying glass) in two distinct areas at a distance of about 22° on opposite sides of the Sun.

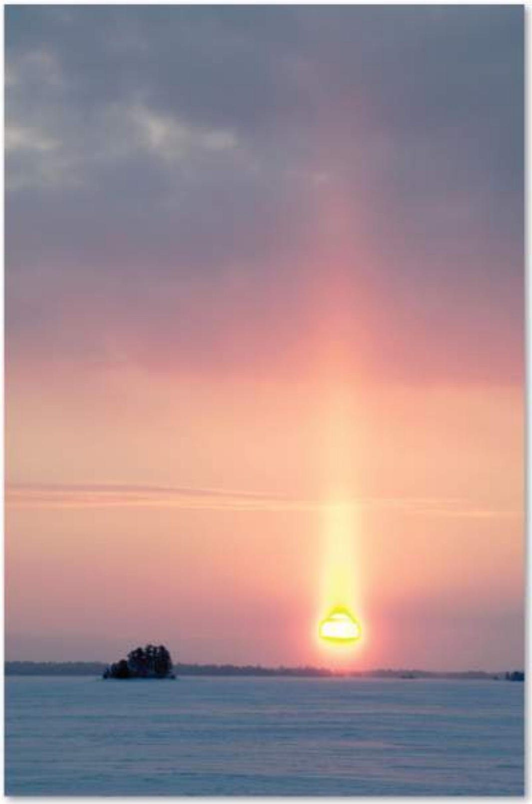
Figure 16.19 Sun dogs

Sun dogs form under the same conditions as, and in conjunction with, halos.

Another optical phenomenon caused by falling ice crystals is **sun pillars**. These vertical shafts of light are most often viewed shortly before sunset or shortly after sunrise, when they appear to extend upward from the Sun (Figure 16.20). These bright pillars of light are created when sunlight is reflected toward the observer from the base (bottom) of descending ice crystals that have plate-like shapes oriented like slowly falling leaves. Because direct sunlight is often reddish when the Sun is low in the sky, pillars appear similarly colored. Occasionally, pillars that extend below the Sun can also be viewed.

Figure 16.20 Sun pillars

A Sun pillar is a concentrated shaft of sunlight that is reflected off the bases of platy ice crystals in cold clouds.



Concept Checks 16.4

- How are halos and rainbows similar?
- In what two ways are halos and rainbows different?
- What is the orientation of the ice crystals that produce a halo? Sun dogs?

16.5 Other Optical Phenomena

LO 5 Compare and contrast coronas and halos.

Thus far, we have considered optical phenomena produced when light is reflected and/or refracted (bent) as it travels through a medium such as air, water, or ice crystals. Optical phenomena are also produced when light is bent as it passes around the surface of small objects, such as tiny cloud droplets—a process called **diffraction**. Diffraction is described as the interference of any type of wave (here we are concerned with light waves) as it passes near an obstacle comparable in size to its wavelength. Like refraction, diffraction separates white light into the colors of the rainbow.

> Bending of light around the surface of an object is called *diffraction*.

Two related optical phenomena produced by diffraction are coronas and iridescent clouds. Another optical phenomenon known as a *glory* is thought to involve reflection, refraction, and diffraction (Box 16.2).

Box 16.2

Glories

A *glory* is a spectacle that is rarely witnessed by observers at Earth's surface. However, the next time you are in an airplane and have a window seat, look for the shadow of your aircraft projected on the clouds below. The airplane's shadow is often surrounded by one or more colored rings that constitute a glory (Figure 16.B). Each ring will be colored in a manner similar to a rainbow, with red being the outermost band and violet the innermost. Generally, however, the colors are not as discernible as those of a rainbow. When two or more sets of rings are seen, the inner one will be the brightest and thinnest.

Figure 16.B Glory

The colored rings of a glory surround the shadow of an airplane projected on the clouds below.

Glories have been observed for centuries and are named for their similar appearance to the iconic halos often seen in religious paintings. In China, this phenomenon is commonly called *Buddha's light*.

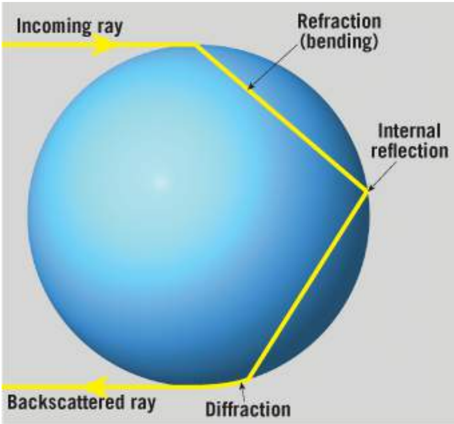
Although it is airplane pilots who most commonly see glories, hikers may also see glories when they climb above a cloud or fog layer and have the Sun at their backs. When a hiker's shadow is cast on the cloud or fogbank, the glory will enshroud the observer's head. If two or more persons experience a glory simultaneously, they see only their own shadow surrounded by their own glory.

Glories form by backscattered light in a manner similar to rainbows. However, the cloud droplets that are responsible for glories are much smaller and more uniform in size than the raindrops that produce rainbows.

The scientific explanation of how glories form is still being debated. One hypothesis is that the light that becomes the glory strikes the outer edge of a cloud droplet. It is then refracted and travels to the back of the droplet, as shown in Figure 16.C. After reflecting off the back of the droplet, the light ray exits on the opposite side from where it entered. This is similar to the way raindrops produce a primary rainbow. However, to produce a glory, the Sun's rays must be bent about 180°, such that they are backscattered directly toward the Sun. Diffraction is one mechanism that is thought to cause the additional bending needed. Because glories always form opposite the Sun's position, the observer's shadow (or the shadow of the airplane the observer is in) will always be found within a glory.

Figure 16.C Formation of a glory

A glory forms when the Sun's rays strike small, uniform cloud droplets.



Apply What You Know

1. Explain the origin of the term *glory*.
2. What material interacts with sunlight to produce a glory?

Coronas

A **corona** most often appears as a bright whitish disk centered on the Moon or Sun. When colors are discernible, the central white disk of the corona is surrounded by one or more concentric rings that exhibit the colors of the rainbow (Figure 16.21). Unique features of coronas include the possible repetition of the corona color sequence and the fact that they are one of the few optical phenomena observed around the Moon more frequently than around the Sun.

Figure 16.21 Coronas

A. Most coronas appear as a bright whitish disk centered on the Moon or Sun. **B.** Coronas that display the colors of the rainbow are rare.

A corona is produced when a thin layer of clouds, often altostratus or cirrostratus, veils the illuminating body (Sun or Moon). When the droplets (or sometimes ice crystals) that produce coronas are tiny and uniform in size, diffraction more effectively separates the white light source into the colors of the rainbow. As a result, the coronas generated by these clouds tend to consist of rings that are easily discernible and have the most distinct colors. Coronas produced by larger cloud droplets tend to have muted colors that appear washed out, giving the corona a whitish appearance.

Coronas can be easily distinguished from 22° halos because their color sequence is bluish-white on the inside and reddish on the outside—opposite the halo color sequence. Coronas also form closer to the illuminating body than do halos.

Iridescent Clouds

Iridescent clouds are among the more spectacular and elusive of optical phenomena. Cloud iridescence, most often associated with altostratus, cirrocumulus, or lenticular clouds, appears as areas of bright colors—violet, pink, and green—generally seen near the edges of a cloud (Figure 16.22). Common examples of iridescence are the spectrum of colors reflected from soap bubbles and from a thin layer of gasoline spilled on a wet surface.

Figure 16.22 **Iridescent cloud**

Eye on the Atmosphere 16.2

The accompanying image of noctilucent clouds was taken over Bilund, Denmark, on July 15, 2010. *Noctilucent clouds* are thin, wavy clouds that form high in the atmosphere (50–53 miles above Earth) and are observed only for a short time after sunset. Because they are observed only at high latitudes and lie within the mesosphere, they are also known as *polar mesospheric clouds.* Because these usually high clouds are more common today than in the past, some researchers have suggested that they may be a result of climate change.

Apply What You Know

1. Explain how noctilucent clouds might be illuminated so they are visible to an Earthbound observer after sunset.
2. Do you think noctilucent clouds are composed of water droplets or ice crystals?

As with the corona shown in Figure 16.21B, the display of colors associated with iridescent clouds is produced by the diffraction of sunlight or moonlight by small, uniform cloud droplets or occasionally small ice crystals. The best time to view iridescent clouds is when the Sun is behind a cloud or just after the Sun has set behind a building or topographic barrier.

Table 16.1 summarizes the basic optical phenomena described in this chapter, based on what process caused them—reflection and/or refraction or diffraction. The table also includes the optical phenomena produced by scattering, which are described in Chapter 2.

Table 16.1 Atmospheric Optical Phenomena

Process	Optical Phenomena	Medium
Refraction	Mirages Halos Sun dogs	Air Ice crystals Ice crystals
Reflection	Sun pillars	Ice crystals
Reflection and refraction	Rainbows	Raindrops
Diffraction	Coronas Iridescent clouds	Cloud droplets Cloud droplets
Scattering	Blue skies Red sunsets	Air Air

Concept Checks 16.5

- What process is responsible for the colors exhibited by coronas and iridescent clouds?
- How can coronas be distinguished from 22° halos?

Concepts in Review

16.1 Interactions of Light and Matter

LO 1 Explain the principle called the *law of reflection* and discuss how refraction causes white light to separate into the spectrum of colors.

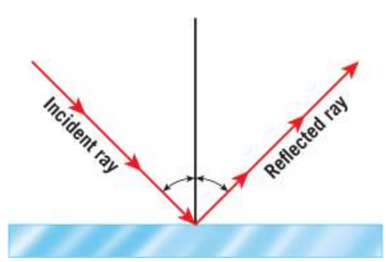
Key Terms

law of reflection

internal reflection

refraction

- The two basic interactions of light with matter are reflection and refraction. The law of reflection states that when light rays are reflected, they bounce off the reflecting surface at the same angle (the angle of reflection) at which they meet that surface (the angle of incidence).
- Refraction is the bending of light due to a change in velocity as it passes obliquely from one transparent medium to another. Furthermore, light will gradually bend as it traverses a layer of air that varies in density.



16.2 Mirages

LO 2 Describe how inferior and superior mirages form.

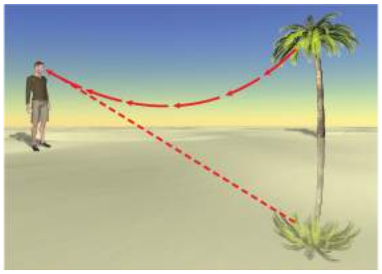
Key Terms

mirage

inferior mirage

superior mirage

- A mirage is an optical effect of the atmosphere caused by refraction when light passes through air with different densities, causing objects to appear displaced from their true position.
- An inferior mirage produces an image that appears below its true location.
- When the refraction of light is significant enough to make an object appear suspended above the horizon, it is called a superior mirage. Another type of mirage, known as Fata Morgana, produces large towering images.



16.3 Rainbows

LO 3 Sketch a raindrop and show how sunlight travels through it to form a primary rainbow.

Key Terms

rainbow

dispersion

- Perhaps the most spectacular and most commonly known atmospheric optical phenomenon is the rainbow. A rainbow forms when raindrops act as prisms and disperse the sunlight into the spectrum of colors in a process called dispersion.
- In a primary rainbow, sunlight is reflected (internal reflection) once within a raindrop. In a dimmer, less frequently observed secondary rainbow, light is reflected twice within a raindrop.

16.4 Halos, Sun Dogs, and Solar Pillars

LO 4 Distinguish among three different optical phenomena that are produced as a result of the interaction between sunlight and hexagonal ice crystals.

Key Terms

halo

sun dogs

sun pillar

- A halo is a narrow whitish ring centered on the Sun. Halos occur most often when the sky is covered with a thin layer of cirrostratus clouds. Halos are produced by the refraction of sunlight by ice crystals.
- A spectacular effect associated with a halo is sun dogs. These two bright regions, or mock suns, can be seen adjacent to a 22° halo.

16.5 Other Optical Phenomena

LO 5 Compare and contrast coronas and halos.

Key Terms

diffraction

corona

iridescent cloud

- Coronas are bright whitish disks centered on the Moon or Sun. They are more commonly witnessed in association with the Moon than with the Sun.
- Iridescent clouds are formed by diffraction of white light by tiny, uniform cloud droplets or, sometimes, ice crystals.

Exercises and Online Activities

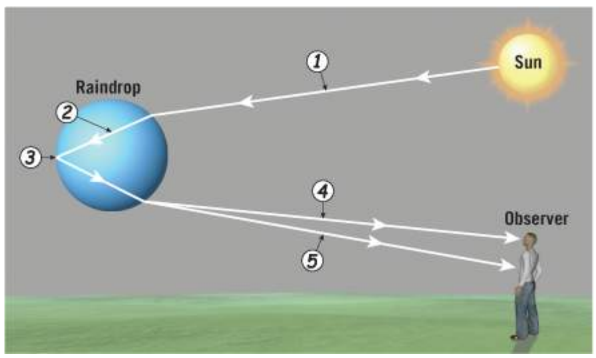
Mastering Meteorology™
For instructor-assigned homework, test prep resources, and other learning materials, visit **Mastering Meteorology.**

Review Questions

1. What is the difference between reflection and refraction?
2. What role does refraction play in the creation of a mirage?
3. How is the formation of an inferior mirage different from that of a superior mirage?
4. Explain why a mirage disappears when the observer nears the mirage.
5. Explain the role of reflection and refraction in producing a primary rainbow.
6. How is the formation of a primary rainbow different from that of a secondary rainbow?
7. Describe how halos, sun dogs, and sun pillars form.
8. What optical phenomena are caused by diffraction?
9. What is iridescence?

Give It Some Thought

1. What particles (cloud droplets, raindrops, or ice crystals) are usually associated with each of these optical phenomena: rainbows, halos, coronas, glories, and sun dogs?
2. The accompanying drawing illustrates how white sunlight is separated into the colors of the rainbow. Match the features numbered 1 through 5 with the following terms: *internal reflection*, *red light*, *violet light*, *incident ray*, and *refracted ray*.



3. If you have ever been close to a large movie theater screen, you may have noticed that the screen is made of small glassy particles oriented at slightly different angles rather than one very smooth surface. Based on what you know about how light is reflected from various surfaces, why do you think this type of screen is used?
4. Explain why the refraction of sunlight causes the length of daylight to be longer than if the Earth had no atmosphere.
5. Name the optical phenomena shown in the accompanying photos.

A.

B.

C.

Beyond the Textbook

1. Optical Phenomena

Go to www.youtube.com and find at least one video for each of these atmospheric phenomena: (1) atmospheric sun dogs, (2) atmospheric sun pillars, and (3) atmospheric halo. As you watch the videos, write a short synopsis (two to three sentences) of each. Copy and paste the URLs of the videos you viewed along with your video summaries into a Word document for your instructor—all your information should be in *one* document.

2. Identifying Optical Phenomena from Photographs

Go to https://www.weathervideohd.tv and find at least one photo example of each atmospheric optical phenomenon listed below. You can find images by checking the box marked Photos in the blue box located near the top left. Then click on the pull-down menu labeled Anticrepuscular Rays, click on the optical phenomenon you are looking for, and hit the Search button just below. (*Note:* Search for one optical phenomenon at a time.) Scroll through to find an image that is similar to the one in your textbook. Download the image by clicking on the blue Download button in the lower right. Then paste the image into a Word document along with a brief description of the optical phenomenon shown. Optical phenomena: (1) corona, (2) glories, (3) green flash, (4) halo, (5) mirages, (6) rainbow, (7) double rainbow, (8) sun dog, and (9) sun pillar.

Appendix A: Metric Units

Table A.1 The International System of Units (SI)

I. Basic units

Quantity	Unit	SI symbol
Length	meter	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Thermodynamic temperature	kelvin	K
Amount of substance	mole	mol
Luminous intensity	candela	cd

II. Prefixes

Prefix	Factor by which unit is multiplied	Symbol
tera	10^{12}	T
giga	10^{9}	G
mega	10^{6}	M
kilo	10^{3}	k
hecto	10^{2}	h
deka	10	da
deci	10^{-1}	d
centi	10^{-2}	c
milli	10^{-3}	m
micro	10^{-6}	μ
nano	10^{-9}	n
pico	10^{-12}	p
femto	10^{-15}	f
atto	10^{-18}	a

III. Derived units

Quantity	Units	Expression
Area	square meter	m^2
Volume	cubic meter	m^3
Frequency	hertz (Hz)	s^{-1}
Density	kilograms per cubic meter	kg/m^3
Velocity	meters per second	m/s
Angular velocity	radians per second	rad/s
Acceleration	meters per second squared	m/s^2
Angular acceleration	radians per second squared	rad/s^2
Force	newton (N)	$kg \cdot ms^2$
Pressure	newtons per square meter	N/m^2
Work, energy, quantity of heat	joule (J)	$N \cdot m$
Power	watt (W)	J/s
Electric charge	coulomb (C)	$A \cdot s$
Voltage, potential difference, electromotive force	volt (V)	W/A
Luminance	candelas per square meter	cd/m^2

Table A.2 **Metric–English Conversion**

When you want to convert to	Multiply by:	To find:
Length		
inches	2.54	centimeters
centimeters	0.39	inches
feet	0.30	meters
meters	3.28	feet
yards	0.91	meters
meters	1.09	yards
miles	1.61	kilometers
kilometers	0.62	miles
Area		
square inches	6.45	square centimeters
square centimeters	0.15	square inches
square feet	0.09	square meters
square meters	10.76	square feet
square miles	2.59	square kilometers
square kilometers	0.39	square miles
Volume		
cubic inches	16.38	cubic centimeters
cubic centimeters	0.06	cubic inches
cubic feet	0.028	cubic meters
cubic meters	35.3	cubic feet
cubic miles	4.17	cubic kilometers
cubic kilometers	0.24	cubic miles
liters	1.06	quarts
liters	0.26	gallons
gallons	3.78	liters
Masses and Weights		
ounces	28.33	grams
grams	0.035	ounces
pounds	0.45	kilograms
kilograms	2.205	pounds
Temperature		
When you want to convert degrees Fahrenheit (°F) to degrees Celsius (°C), subtract 32 degrees and divide by 1.8 (also see Table A–3).		
When you want to convert degrees Celsius (°C) to degrees Fahrenheit (°F), multiply by 1.8 and add 32 degrees (also see Table A–3).		
When you want to convert degrees Celsius (°C) to kelvins (K), delete the degree symbol and add 273.		
When you want to convert kelvins (K) to degrees Celsius (°C), add the degree symbol and subtract 273.		

Table A.3 Temperature Conversion Table. (To find either the Celsius or the Fahrenheit equivalent, locate the known temperature in the center column. Then read the desired equivalent value from the appropriate column.)

°C		°F	°C		°F	°C		°F	°C		°F
−40.0	−40	−40	−17.2	+1	33.8	5.0	41	105.8	27.2	81	177.8
−39.4	−39	−38.2	−16.7	2	35.6	5.6	42	107.6	27.8	82	179.6
−38.9	−38	−36.4	−16.1	3	37.4	6.1	43	109.4	28.3	83	181.4
−38.3	−37	−34.6	−15.4	4	39.2	6.7	44	111.2	28.9	84	183.2
−37.8	−36	−32.8	−15.0	5	41.0	7.2	45	113.0	29.4	85	185.0
−37.2	−35	−31.0	−14.4	6	42.8	7.8	46	114.8	30.0	86	186.8
−36.7	−34	−29.2	−13.9	7	44.6	8.3	47	116.6	30.6	87	188.6
−36.1	−33	−27.4	−13.3	8	46.4	8.9	48	118.4	31.1	88	190.4
−35.6	−32	−25.6	−12.8	9	48.2	9.4	49	120.2	31.7	89	192.2
−35.0	−31	−23.8	−12.2	10	50.0	10.0	50	122.0	32.2	90	194.0
−34.4	−30	−22.0	−11.7	11	51.8	10.6	51	123.8	32.8	91	195.8
−33.9	−29	−20.2	−11.1	12	53.6	11.1	52	125.6	33.3	92	197.6
−33.3	−28	−18.4	−10.6	13	55.4	11.7	53	127.4	33.9	93	199.4
−32.8	−27	−16.6	−10.0	14	57.2	12.2	54	129.2	34.4	94	201.2
−32.2	−26	−14.8	−9.4	15	59.0	12.8	55	131.0	35.0	95	203.0
−31.7	−25	−13.0	−8.9	16	60.8	13.3	56	132.8	35.6	96	204.8
−31.1	−24	−11.2	−8.3	17	62.6	13.9	57	134.6	36.1	97	206.6
−30.6	−23	−9.4	−7.8	18	64.4	14.4	58	136.4	36.7	98	208.4
−30.0	−22	−7.6	−7.2	19	66.2	15.0	59	138.2	37.2	99	210.2
−29.4	−21	−5.8	−6.7	20	68.0	15.6	60	140.0	37.8	100	212.0
−28.9	−20	−4.0	−6.1	21	69.8	16.1	61	141.8	38.3	101	213.8
−28.3	−19	−2.2	−5.6	22	71.6	16.7	62	143.6	38.9	102	215.6
−27.8	−18	−0.4	−5.0	23	73.4	17.2	63	145.4	39.4	103	217.4
−27.2	−17	+1.4	−4.4	24	75.2	17.8	64	147.2	40.0	104	219.2
−26.7	−16	3.2	−3.9	25	77.0	18.3	65	149.0	40.6	105	221.0
−26.1	−15	5.0	−3.3	26	78.8	18.9	66	150.8	41.1	106	222.8
−25.6	−14	6.8	−2.8	27	80.6	19.4	67	152.6	41.7	107	224.6
−25.0	−13	8.6	−2.2	28	82.4	20.0	68	154.4	42.2	108	226.4
−24.4	−12	10.4	−1.7	29	84.2	20.6	69	156.2	42.8	109	228.2
−23.9	−11	12.2	−1.1	30	86.0	21.1	70	158.0	43.3	110	230.0
−23.3	−10	14.0	−0.6	31	87.8	21.7	71	159.8	43.9	111	231.8
−22.8	−9	15.8	0.0	32	89.6	22.2	72	161.6	44.4	112	233.6
−22.2	−8	17.6	+0.6	33	91.4	22.8	73	163.4	45.0	113	235.4
−21.7	−7	19.4	1.1	34	93.2	23.3	74	165.2	45.6	114	237.2
−21.1	−6	21.2	1.7	35	95.0	23.9	75	167.0	46.1	115	239.0
−20.6	−5	23.0	2.2	36	96.8	24.4	76	168.8	46.7	116	240.8
−20.0	−4	24.8	2.8	37	98.6	25.0	77	170.6	47.2	117	242.6
−19.4	−3	26.6	3.3	38	100.4	25.6	78	172.4	47.8	118	244.4
−18.9	−2	28.4	3.9	39	102.2	26.1	79	174.2	48.3	119	246.2
−18.3	−1	30.2	4.4	40	104.0	26.7	80	176.0	48.9	120	248.0
−17.8	0	32.0									

Table A.4 Wind-Conversion Table (Wind-Speed Units: 1 Mile Per Hour = 0.868391 Knot 1.609344 km/h = 0.44704 m/s)

Miles per Hour	Knots	Meters per Second	Kilometers per Hour	Miles per Hour	Knots	Meters per Second	Kilometers per Hour
1	0.9	0.4	1.6	51	44.3	22.8	82.1
2	1.7	0.9	3.2	52	45.2	23.2	83.7
3	2.6	1.3	4.8	53	46.0	23.7	85.3
4	3.5	1.8	6.4	54	46.9	24.1	86.9
5	4.3	2.2	8.0	55	47.8	24.6	88.5
6	5.2	2.7	9.7	56	48.6	25.0	90.1
7	6.1	3.1	11.3	57	49.5	25.5	91.7
8	6.9	3.6	12.9	58	50.4	25.9	93.3
9	7.8	4.0	14.5	59	51.2	26.4	95.0
10	8.7	4.5	16.1	60	52.1	26.8	96.6
11	9.6	4.9	17.7	61	53.0	27.3	98.2
12	10.4	5.4	19.3	62	53.8	27.7	99.8
13	11.3	5.8	20.9	63	54.7	28.2	101.4
14	12.2	6.3	22.5	64	55.6	28.6	103.0
15	13.0	6.7	24.1	65	56.4	29.1	104.6
16	13.9	7.2	25.7	66	57.3	29.5	106.2
17	14.8	7.6	27.4	67	58.2	30.0	107.8
18	15.6	8.0	29.0	68	59.1	30.4	109.4
19	16.5	8.5	30.6	69	59.9	30.8	111.0
20	17.4	8.9	32.2	70	60.8	31.3	112.7
21	18.2	9.4	33.8	71	61.7	31.7	114.3
22	19.1	9.8	35.4	72	62.5	32.2	115.9
23	20.0	10.3	37.0	73	63.4	32.6	117.5
24	20.8	10.7	38.6	74	64.3	33.1	119.1
25	21.7	11.2	40.2	75	65.1	33.5	120.7
26	22.6	11.6	41.8	76	66.0	34.0	122.3
27	23.4	12.1	43.5	77	66.9	34.4	123.9
28	24.3	12.5	45.1	78	67.7	34.9	125.5
29	25.2	13.0	46.7	79	68.6	35.3	127.1
30	26.1	13.4	48.3	80	69.5	35.8	128.7
31	26.9	13.9	49.9	81	70.3	36.2	130.4
32	27.8	14.3	51.5	82	71.2	36.7	132.0
33	28.7	14.8	53.1	83	72.1	37.1	133.6
34	29.5	15.2	54.7	84	72.9	37.6	135.2
35	30.4	15.6	56.3	85	73.8	38.0	136.8
36	31.3	16.1	57.9	86	74.7	38.4	138.4
37	32.1	16.5	59.5	87	75.5	38.9	140.0
38	33.0	17.0	61.2	88	76.4	39.3	141.6
39	33.9	17.4	62.8	89	77.3	39.8	143.2
40	34.7	17.9	64.4	90	78.2	40.2	144.8
41	35.6	18.3	66.0	91	79.0	40.7	146.5
42	36.5	18.8	67.6	92	79.9	41.1	148.1

(Continued)

TABLE A.4 *(Continued)*

Miles per Hour	Knots	Meters per Second	Kilometers per Hour	Miles per Hour	Knots	Meters per Second	Kilometers per Hour
43	37.3	19.2	69.2	93	80.8	41.6	149.7
44	38.2	19.7	70.8	94	81.6	42.0	151.3
45	39.1	20.1	72.4	95	82.5	42.5	152.9
46	39.9	20.6	74.0	96	83.4	42.9	154.5
47	40.8	21.0	75.6	97	84.2	43.4	156.1
48	41.7	21.5	77.2	98	85.1	43.8	157.7
49	42.6	21.9	78.9	99	86.0	44.3	159.3
50	43.4	22.4	80.5	100	86.8	44.7	160.9

Appendix B: Explanation and Decoding of the Daily Weather Map

Weather maps showing the development and movement of weather systems are among the most important tools used by the meteorologist. Some maps portray conditions near Earth's surface, and others depict conditions at various heights in the atmosphere. Some cover the entire Northern Hemisphere, and others cover only local areas as required for special purposes.

Principal Surface Weather Map

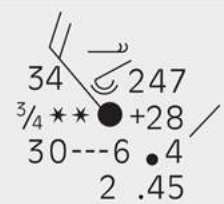
To prepare the surface map and present the information quickly and pictorially, two actions are necessary: (1) Weather observers and automated observing stations must send data to the offices where the maps are prepared; and (2) the information must be quickly transcribed to the maps. To achieve the necessary speed and economy of space and transmission time, codes have been devised for sending the information and for plotting it on the maps.

Codes and Map Plotting

A great deal of information is contained in a brief coded weather message. If each item were named and described in plain language, a very lengthy message would be required, one confusing to read and difficult to transfer to a map. A code permits the message to be condensed to a few five-figure numeral groups, each figure of which has a meaning, depending on its position in the message. People trained in the use of the code can read the message as easily as plain language (Table B.1).

Table B.1 Explanation of Station Symbols and Map Entries

Symbol station model



Sample report

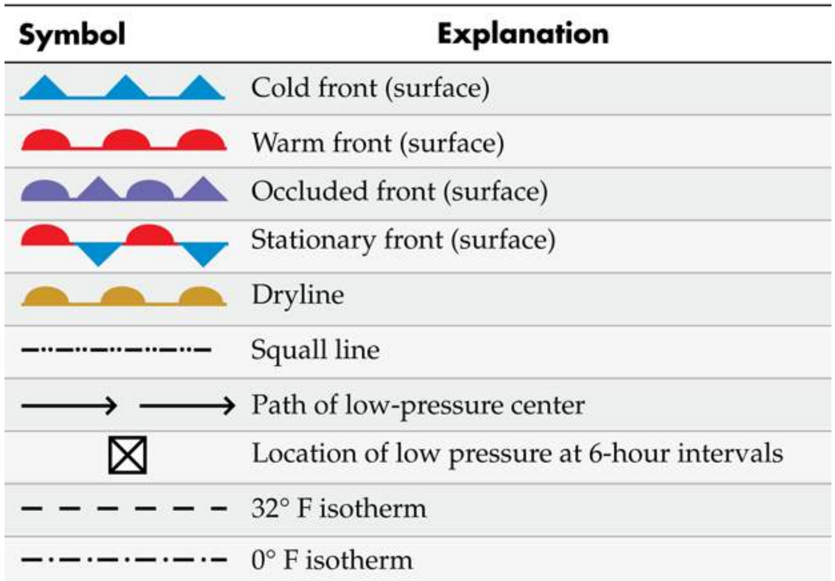
N	Total cloud cover—Table B.7
dd	Wind direction
ff	Wind speed in knots or mi/hr—Table B.8
VV	Visibility in miles
ww	Present weather—Table B.9
W	Past weather—Table B.9
PPP	Barometric pressure reduced to sea level (add an initial 9 or 10 and place a decimal point to the left of last number)
TT	Current air temperature in °F
N_h	Fraction of sky covered by low or middle clouds—Table B.7 (ranges from 0 for no clouds to 9 for sky obscured)
C_L	Low clouds or clouds with vertical development—Table B.5
h	Height in feet of the base of the lowest clouds—Table B.6
C_M	Middle clouds—Table B.5
C_H	High clouds—Table B.5
T_dT_d	Dew point temperature in °F
a	Pressure tendency—Table B.3
pp	Pressure change in mb in preceding 3 hrs(+28 = +2.8)
RR	Amount of precipitation in last 6 hr
R_t	Time precipitation began or ended (0 = none; 1= <1 hr ago; 2 = 1–2 hr ago; 3 = 2–3 hr ago; 4 = 3–4 hr ago; 5 = 4–5 hr ago; 6 = 5–6 hr ago; 7 = 6–12 hr ago; 8 = >12 hr ago; 9 = unknown)

The location of the reporting station is printed on the map as a small circle (the station circle). A definite arrangement of the data around the station circle, called the *station model*, is used. When the report is plotted in these fixed positions around the station circle on the weather map, many code figures are transcribed exactly as sent. Entries in the station model that are not made in code figures or actual values found in the message are usually in the form of symbols that graphically represent the element concerned. In some cases, certain of the data may or may not be reported by the observer, depending on local weather conditions. Precipitation and clouds are examples. In such cases, the absence of an entry on the map is interpreted as nonoccurrence or nonobservance of the phenomena. The letter *M* is entered where data are normally observed but not received.

Both the code and the station model are based on international agreements. These standardized numerals and symbols enable a meteorologist of one country to use the weather reports and weather maps of another country even though that person does not understand the language. Weather codes are, in effect, an international language that permits complete interchange and use of worldwide weather reports so essential in present-day activities.

The boundary between two different air masses is called a *front*. Important changes in weather, temperature, wind direction, and clouds often occur with the passage of a front. Half circles or triangular symbols or both are placed on the lines representing fronts to indicate the kind of front. The side on which the symbols are placed indicates the direction of frontal movement. The boundary of relatively cold air of polar origin advancing into an area occupied by warmer air, often of tropical origin, is called a *cold front*. The boundary of relatively warm air advancing into an area occupied by colder air is called a *warm front*. The line along which a cold front has overtaken a warm front at the ground is called an *occluded front*. A boundary between two air masses, which shows at the time of observation little tendency to advance into either the warm or cold areas, is called a *stationary front*. Air-mass boundaries are known as *surface fronts* when they intersect the ground and as *upper-air fronts* when they do not. Surface fronts are drawn in solid black; fronts aloft are drawn in outline only. Front symbols are given in Table B.2.

Table B.2 Weather Map Symbols



Symbol	Explanation
	Cold front (surface)
	Warm front (surface)
	Occluded front (surface)
	Stationary front (surface)
	Dryline
	Squall line
	Path of low-pressure center
	Location of low pressure at 6-hour intervals
	32° F isotherm
	0° F isotherm

A front that is disappearing or weak and decreasing in intensity is labeled *frontolysis*. A front that is forming is labeled *frontogenesis*. A *squall line* is a line of thunderstorms or squalls usually accompanied by heavy showers and shifting winds (Table B.2).

The paths followed by individual disturbances are called *storm tracks* and are shown by arrows (Table B.1). A symbol (a box containing an X) indicates past positions of a low-pressure center at 6-hour intervals. HIGH (H) and LOW (L) indicate the centers of high and low barometric pressure. Solid lines are isobars and connect points of equal sea-level barometric pressure. The spacing and orientation of these lines on weather maps are indications of speed and direction of wind flow. In general, wind direction is parallel to these lines with low pressure to the left of an observer looking downwind. Speed is directly proportional to the closeness of the lines (called *pressure gradient*). Isobars are labeled in millibars.

Isotherms are lines connecting points of equal temperature. Two isotherms are frequently drawn on large surface weather maps when applicable. The freezing, or 32°F, isotherm is drawn as a dashed line, and the 0°F isotherm is drawn as a dash–dot line (Table B.2). Areas where precipitation is occurring at the time of observation are shaded.

Auxiliary Maps

500-Millibar Map

Contour lines, isotherms, and wind arrows are shown on the 500-millibar contour level. Solid lines are drawn to show height above sea level and are labeled in feet. Dashed lines are drawn at 5° intervals of temperature and are labeled in degrees Celsius. True wind direction is shown by "arrows" that indicate the direction from which the wind is blowing. The wind speed is shown by flags and feathers. Each flag represents 50 knots, each full feather represents 10 knots, and each half feather represents 5 knots.

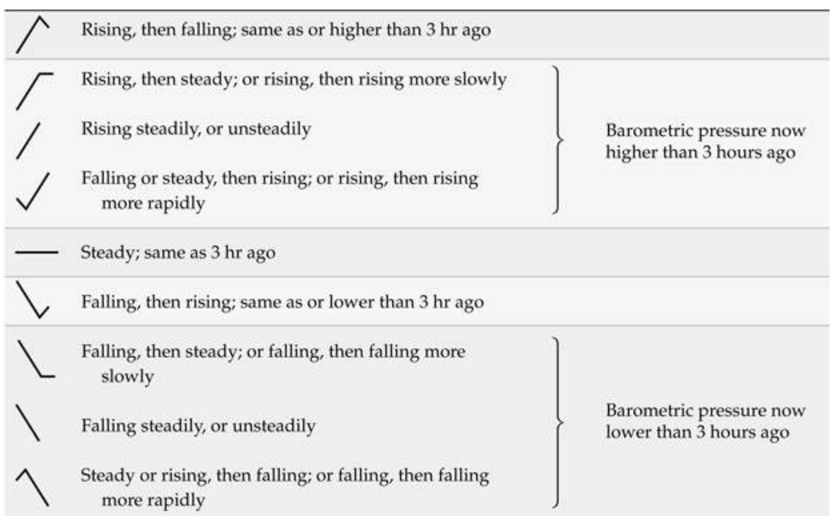
Temperature Map (Highest and Lowest)

Temperature data are entered from selected weather stations in the United States. The figure entered above the station dot shows the maximum temperature for the 12-hour period ending 7:00 P.M. EST of the previous day. The figure entered below the station dot shows the minimum temperature during the 12 hours ending at 7:00 A.M. EST. The letter *M* denotes missing data.

Precipitation Map

Precipitation data are entered from selected weather stations in the United States. When precipitation has occurred at any of these stations in the 24-hour period ending at 7:00 A.M. EST, the total amount, in inches and hundredths, is entered above the station dot. When the figures for total precipitation have been compiled from incomplete data and entered on the map, the amount is underlined. *T* indicates a trace of precipitation (less than 0.01 inch) and the letter *M* denotes missing data. The geographical areas where precipitation has fallen during the 24 hours ending at 7:00 A.M. EST are shaded. Dashed lines show depth of snow on ground in inches as of 7:00 A.M. EST.

Table B.3 Air Pressure Tendency

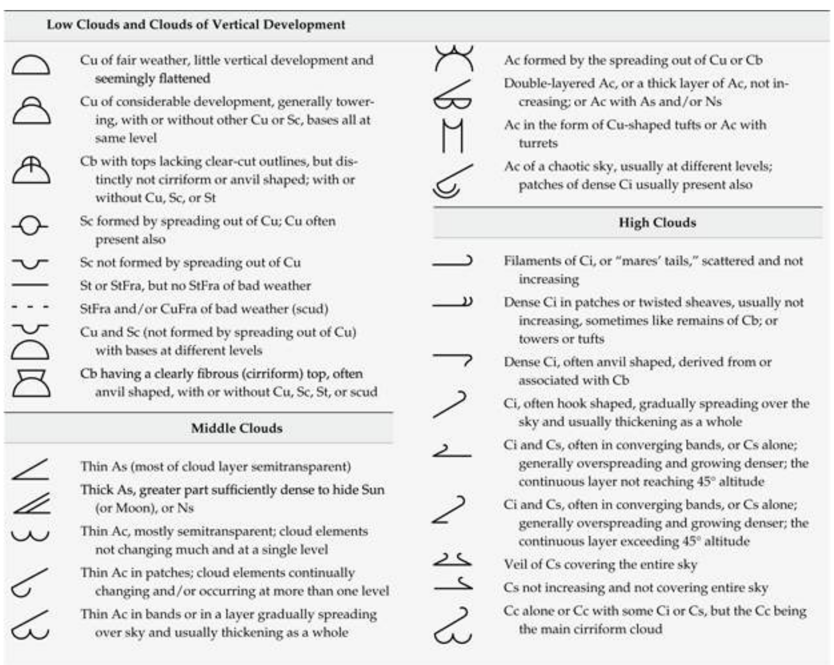


	Rising, then falling; same as or higher than 3 hr ago	
	Rising, then steady; or rising, then rising more slowly	Barometric pressure now higher than 3 hours ago
	Rising steadily, or unsteadily	
	Falling or steady, then rising; or rising, then rising more rapidly	
	Steady; same as 3 hr ago	
	Falling, then rising; same as or lower than 3 hr ago	
	Falling, then steady; or falling, then falling more slowly	Barometric pressure now lower than 3 hours ago
	Falling steadily, or unsteadily	
	Steady or rising, then falling; or falling, then falling more rapidly	

Table B.4 Cloud Abbreviations

St	stratus
Fra	fractus
Sc	stratocumulus
Ns	nimbostratus
As	altostratus
Ac	altocumulus
Ci	cirrus
Cs	cirrostratus
Cc	cirrocumulus
Cu	cumulus
Cb	cumulonimbus

Table B.5 Cloud Types



Low Clouds and Clouds of Vertical Development
Cu of fair weather, little vertical development and seemingly flattened
Cu of considerable development, generally towering, with or without other Cu or Sc, bases all at same level
Cb with tops lacking clear-cut outlines, but distinctly not cirriform or anvil shaped; with or without Cu, Sc, or St
Sc formed by spreading out of Cu; Cu often present also
Sc not formed by spreading out of Cu
St or StFra, but no StFra of bad weather
StFra and/or CuFra of bad weather (scud)
Cu and Sc (not formed by spreading out of Cu) with bases at different levels
Cb having a clearly fibrous (cirriform) top, often anvil shaped, with or without Cu, Sc, St, or scud
Middle Clouds
Thin As (most of cloud layer semitransparent)
Thick As, greater part sufficiently dense to hide Sun (or Moon), or Ns
Thin Ac, mostly semitransparent; cloud elements not changing much and at a single level
Thin Ac in patches; cloud elements continually changing and/or occurring at more than one level
Thin Ac in bands or in a layer gradually spreading over sky and usually thickening as a whole
Ac formed by the spreading out of Cu or Cb
Double-layered Ac, or a thick layer of Ac, not increasing; or Ac with As and/or Ns
Ac in the form of Cu-shaped tufts or Ac with turrets
Ac of a chaotic sky, usually at different levels; patches of dense Ci usually present also
High Clouds
Filaments of Ci, or "mares' tails," scattered and not increasing
Dense Ci in patches or twisted sheaves, usually not increasing, sometimes like remains of Cb; or towers or tufts
Dense Ci, often anvil shaped, derived from or associated with Cb
Ci, often hook shaped, gradually spreading over the sky and usually thickening as a whole
Ci and Cs, often in converging bands, or Cs alone; generally overspreading and growing denser; the continuous layer not reaching 45° altitude
Ci and Cs, often in converging bands, or Cs alone; generally overspreading and growing denser; the continuous layer exceeding 45° altitude
Veil of Cs covering the entire sky
Cs not increasing and not covering entire sky
Cc alone or Cc with some Ci or Cs, but the Cc being the main cirriform cloud

Table B.6 **Height of Base of Lowest Cloud**

Code	Feet	Meters
0	0–149	0–49
1	150–299	50–99
2	300–599	100–199
3	600–999	200–299
4	1000–1999	300–599
5	2000–3499	600–999
6	3500–4999	1000–1499
7	5000–6499	1500–1999
8	6500–7999	2000–2499
9	8000 or above or no clouds	2500 or above or no clouds

Table B.7 **Cloud Cover**

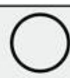
	No clouds
	One-tenth or less
	Two-tenths or three-tenths
	Four-tenths
	Five-tenths
	Six-tenths
	Seven-tenths or eight-tenths
	Nine-tenths or overcast with openings
	Completely overcast (ten-tenths)
	Sky obscured

Table B.8 Wind Speed

	Miles per hour	Knots	Kilometers per hour
	calm	calm	calm
	1–2	1–2	1–3
	3–8	3–7	3–13
	9–14	8–12	14–19
	15–20	8–12	14–19
	21–25	18–22	14–19
	26–31	23–27	41–50
	32–37	28–32	51–60
	38–43	33–37	61–69
	44–49	38–42	70–79
	50–54	43–47	80–87
	55–60	48–52	88–96
	61–66	53–57	97–106
	67–71	58–62	107–114
	72–77	63–67	115–124
	78–83	68–72	125–134
	84–89	73–77	135–143
	119–123	103–107	192–198

Table B.9 Weather Conditions

Cloud development NOT observed or NOT observable during past hour	Clouds generally dissolving or becoming less developed during past hour	State of sky on the whole unchanged during past hour	Clouds generally forming or developing during past hour	Visibility reduced by smoke
Light fog (mist)	Patches of shallow fog at station, NOT deeper than 6 feet on land	More or less continuous shallow fog at station, NOT deeper than 6 feet on land	Lightning visible, no thunder heard	Precipitation within sight, but NOT reaching the ground
Drizzle (NOT freezing) or snow grains (NOT falling as showers) during past hour, but NOT at time of observation	Rain (NOT freezing and NOT falling as showers) during past hour, but NOT at time of observation	Snow (NOT falling as showers) during past hour, but NOT at time of observation	Rain and snow or ice pellets (NOT falling as showers) during past hour, but NOT at time of observation	Freezing drizzle or freezing rain (NOT falling as showers) during past hour, but NOT at time of observation
Slight or moderate dust storm or sandstorm has decreased during past hour	Slight or moderate dust storm or sandstorm, no appreciable change during past hour	Slight or moderate dust storm or sandstorm has begun or increased during past hour	Severe dust storm or sandstorm, has decreased during past hour	Severe dust storm or sandstorm, no appreciable change during past hour
Fog or ice fog at distance at time of observation, but NOT at station during past hour	Fog or ice fog in patches	Fog or ice fog, sky discernible, has become thinner during past hour	Fog or ice fog, sky NOT discernible, has become thinner during past hour	Fog or ice fog, sky discernible, no appreciable change during past hour
Intermittent drizzle (NOT freezing), slight at time of observation	Continuous drizzle (NOT freezing), slight at time of observation	Intermittent drizzle (NOT freezing), moderate at time of observation	Continuous drizzle (NOT freezing), moderate at time of observation	Intermittent drizzle (NOT freezing), heavy at time of observation
Intermittent rain (NOT freezing), slight at time of observation	Continuous rain (NOT freezing), slight at time of observation	Intermittent rain (NOT freezing), moderate at time of observation	Continuous rain (NOT freezing), moderate at time of observation	Intermittent rain (NOT freezing), heavy at time of observation
Intermittent fall of snowflakes, slight at time of observation	Continuous fall of snowflakes, slight at time of observation	Intermittent fall of snowflakes, moderate at time of observation	Continuous fall of snowflakes, moderate at time of observation	Intermittent fall of snowflakes, heavy at time of observation
Slight rain shower(s)	Moderate or heavy rain shower(s)	Violent rain shower(s)	Slight shower(s) of rain and snow mixed	Moderate or heavy shower(s) of rain and snow mixed
Moderate or heavy shower(s) of hail, with or without rain, or rain and snow mixed, not associated with thunder	Slight rain at time of observation; thunderstorm during past hour, but NOT at time of observation	Moderate or heavy rain at time of observation; thunderstorm during past hour, but NOT at time of observation	Slight snow, or rain and snow mixed, or hail at time of observation; thunderstorm during past hour, but NOT at time of observation	Moderate or heavy snow, or rain and snow mixed, or hail at time of observation; thunderstorm during past hour, but NOT at time of observation

(Continued)

TABLE G Continued

Haze	Widespread dust in suspension in the air, NOT raised by wind, at time of observation	Dust or sand raised by wind at time of observation	Well developed dust whirl(s) within past hour	Dust storm or sandstorm within sight of or at station during past hour
Precipitation within sight, reaching the ground but distant from station	Precipitation within sight, reaching the ground, near to but NOT at station	Thunderstorm, but no precipitation at the station	Squall(s) within sight during past hour or at time of observation	Funnel cloud(s) within sight of station at time of observation
Showers of rain during past hour, but NOT at time of observation	Showers of snow, or of rain and snow, during past hour, but NOT at time of observation	Showers of hail, or of hail and rain, during past hour, but NOT at time of observation	Fog during past hour, but NOT at time of observation	Thunderstorm (with or without precipitation) during past hour, but NOT at time of observation
Severe dust storm or sandstorm has begun or increased during past hour	Slight or moderate drifting snow, generally low (less than 6 ft)	Heavy drifting snow, generally low	Slight or moderate blowing snow, generally high (more than 6 ft)	Heavy blowing snow, generally high
Fog or ice fog, sky NOT discernible, no appreciable change during past hour	Fog or ice fog, sky discernible, has begun or become thicker during past hour	Fog or ice fog, sky NOT discernible, has begun or become thicker during past hour	Fog depositing rime, sky discernible	Fog depositing rime, sky NOT discernible
Continuous drizzle (NOT freezing), heavy at time of observation	Slight freezing drizzle	Moderate or heavy freezing drizzle	Drizzle and rain, slight	Drizzle and rain, moderate or heavy
Continuous rain (NOT freezing), heavy at time of observation	Slight freezing rain	Moderate or heavy freezing rain	Rain or drizzle and snow, slight	Rain or drizzle and snow, moderate or heavy
Continuous fall of snowflakes, heavy at time of observation	Ice prisms (with or without fog)	Snow grains (with or without fog)	Isolated starlike snow crystals (with or without fog)	Ice pellets or snow pellets
Slight snow shower(s)	Moderate or heavy snow shower(s)	Slight shower(s) of snow pellets, or ice pellets with or without rain, or rain and snow mixed	Moderate or heavy shower(s) of snow pellets, or ice pellets, or ice pellets with or without rain or rain and snow mixed	Slight shower(s) of hail, with or without rain or rain and snow mixed, not associated with thunder
Slight or moderate thunderstorm without hail, but with rain, and/or snow at time of observation	Slight or moderate thunderstorm, with hail at time of observation	Heavy thundestorm, without hail, but with rain and/or snow at time of observation	Thunderstorm combined with dust storm or sandstorm at time of observation	Heavy thunderstorm with hail at time of observation

Appendix C: Relative Humidity and Dew-Point Tables

Table C.1 Relative Humidity (Percent)*

Dry bulb (°C)	Depression of Web-Bulb (Dry-bulb temperature – Wet-bulb temperature = Depression of the wet bulb)																				
Dry-Bulb (Air) Temperature	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
−20	28																					
−18	40																					
−16	48	0																				
−14	55	11																				
−12	61	23																				
−10	66	33	0																			
−8	71	41	13																			
−6	73	48	20	0																		
−4	77	54	32	11																		
−2	79	58	37	20	1																	
0	81	63	45	28	11																	
2	83	67	51	36	20	6																
4	85	70	56	42	27	14																
6	86	72	59	46	35	22	10	0														
8	87	74	62	51	39	28	17	6														
10	88	76	65	54	43	38	24	13	4													
12	88	78	67	57	48	38	28	19	10	2												
14	89	79	69	60	50	41	33	25	16	8	1											
16	90	80	77	62	54	45	37	29	21	14	7	1										
18	91	81	72	64	56	48	40	33	26	19	12	6	0									
20	91	82	74	66	58	51	44	36	30	23	17	11	5									
22	92	83	75	68	60	53	46	40	33	27	21	15	10	4	0							
24	92	84	76	69	62	55	49	42	36	30	25	20	14	9	4	0						
26	92	85	77	70	64	57	51	45	39	34	28	23	18	13	9	5						
28	93	86	78	71	65	59	53	45	42	36	31	26	21	17	12	8	4					
30	93	86	79	72	66	61	55	49	44	39	34	29	25	20	16	12	8	4				
32	93	86	80	73	68	62	56	51	46	41	36	32	27	22	19	14	11	8	4			
34	93	86	81	74	69	63	58	52	48	43	38	34	30	26	22	18	14	11	8	5		
36	94	87	81	75	69	64	59	54	50	44	40	36	32	28	24	21	17	13	10	7	4	
38	94	87	82	76	70	66	60	55	51	46	42	38	34	30	26	23	20	16	13	10	7	5
40	94	89	82	76	71	67	61	57	52	48	44	40	36	33	29	25	22	19	16	13	10	7

Relative Humidity Values

*To determine the relative humidity, find the air (dry-bulb) temperature on the vertical axis (far left) and the depression of the wet bulb on the horizontal axis (top). Where the two meet, the relative humidity is found. For example, when the dry-bulb temperature is 20°C and a wet-bulb temperature is 14°C, then the depression of the wet bulb is 6°C (20°C −14°C). From **TABLE C.1**, the relative humidity is 51 percent and from **TABLE C.2**, the dew point is 10°C.

Table C.2 Dew-Point Temperature (°C)

Dry bulb (°C)	Depression of Web-Bulb (Dry-bulb temperature – Wet-bulb temperature = Depression of the wet bulb)																				
Dry-Bulb (Air) Temperature	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
−20	−33																					
−18	−28																					
−16	−24																					
−14	−21	−36																				
−12	−18	−28																				
−10	−14	−22																				
−8	−12	−18	−29																			
−6	−10	−14	−22																			
−4	−7	−12	−17	−29																		
−2	−5	−8	−13	−20																		
0	−3	−6	−9	−15	−24																	
2	−1	−3	−6	−11	−17																	
4	1	−1	−4	−7	−11	−19																
6	4	1	−1	−4	−7	−13	−21															
8	6	3	1	2	−5	−9	−14															
10	8	6	4	1	−2	−5	−9	−14	−18													
12	10	8	6	4	1	−2	−5	−9	−16													
14	12	11	9	6	4	1	−2	−5	−10	−17												
16	14	13	11	9	7	4	1	−1	−6	−10	−17											
18	16	15	13	11	9	7	4	2	−2	5	10	−19										
20	19	17	15	14	12	10	7	4	2	−2	−5	−10	−19									
22	21	19	17	16	14	12	10	8	5	3	−1	−5	−10	−19								
24	23	21	20	18	16	14	12	10	8	6	2	−1	−5	−10	−18							
26	25	23	22	20	18	17	15	13	11	9	6	3	0	−4	−9	−18						
28	27	25	24	22	27	19	17	16	14	11	9	7	4	1	−3	−9	16					
30	29	27	26	24	23	21	19	18	16	14	12	10	8	5	1	−2	−8	−15				
32	31	29	28	27	25	24	22	21	19	17	15	13	11	8	5	2	−2	−7	−14			
34	33	31	30	29	27	26	24	23	21	20	18	16	14	12	9	6	3	−1	−5	−12	−29	
36	35	33	32	31	29	28	27	25	24	22	20	19	17	15	13	10	7	4	0	−4	−10	
38	37	35	34	33	32	30	29	28	26	25	23	21	19	17	15	13	11	8	5	1	−3	9
40	39	37	36	35	34	32	31	30	28	27	25	24	22	20	18	16	14	12	9	6	2	−2

Dew-Point Values

Table C.3 Relative humidity (°F)*

Dry bulb (°F)	Depression of Web-Bulb (Dry-bulb temperature – Wet-bulb temperature = Depression of the wet bulb)																				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	25	30
0	67	33	1																			
5	73	46	20																			
10	78	56	34	13																		
15	82	64	46	29	11																	
20	85	70	55	40	26	12																
25	87	74	62	49	37	25	13	1														
30	89	78	67	56	46	36	26	16	6													
35	91	81	72	63	54	45	36	27	19	10	2											
40	92	83	75	68	60	52	45	37	29	22	15	7										
45	93	86	78	71	64	57	51	44	38	31	25	18	12	6								
50	93	87	80	74	67	61	55	49	43	38	32	27	21	16	10	5						
55	94	88	82	76	70	65	59	54	49	43	38	33	28	23	19	11	9	5				
60	94	89	83	78	73	68	63	58	53	48	43	39	34	30	26	21	17	13	9	5		
65	95	90	85	80	75	70	66	61	56	52	48	44	39	35	31	27	24	20	16	12		
70	95	90	86	81	77	72	68	64	59	55	51	48	44	40	36	33	29	25	22	19	3	
75	96	91	86	82	78	74	70	66	62	58	54	51	47	44	40	37	34	30	27	24	9	
80	96	91	87	83	79	75	72	68	64	61	57	54	50	47	44	41	38	35	32	29	15	3
85	96	92	88	84	81	77	73	70	66	63	59	57	53	50	47	44	41	38	36	33	20	8
90	96	92	89	85	81	78	74	71	68	65	61	58	55	52	49	47	44	41	39	36	24	13
95	96	93	89	86	82	79	76	73	69	66	63	61	58	55	52	50	47	44	42	39	28	17
100	96	93	89	86	83	80	77	73	70	68	65	62	59	56	54	51	49	46	44	41	30	21
105	97	93	90	87	84	81	78	75	72	69	66	64	61	58	56	53	51	49	46	44	34	24
110	97	93	90	87	84	81	78	75	73	70	67	65	62	60	57	55	52	50	48	46	36	26

*To determine the relative humidity, find the air (dry-bulb) temperature on the vertical axis (far left) and the depression of the wet bulb on the horizontal axis (top). Where the two meet, the relative humidity is found. For example, when the dry-bulb temperature is 70°F and a wet-bulb temperature is 57°F, then the depression of the wet-bulb is 13°F (70°F–57°F). *From Table C.3, the relative humidity is 44 percent and from Table C.4, the dew point is 47°F.*

Table C.4 Dew-Point Temperature (°F)

Dry Bulb (°F)	Depression of Web-Bulb (Dry-bulb temperature – Wet-bulb temperature = Depression of the wet bulb)																				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	25	30
0	−7	−17	−37																			
5	−1	−8	−20																			
10	5	−1	−9	−21																		
15	11	6	0	−8	−20																	
20	16	12	8	2	−6	−17																
25	22	18	15	10	6	−2	−12															
30	27	24	21	17	13	2	−7	−20														
35	36	30	27	24	20	16	12	6	1													
40	38	35	33	30	27	24	20	16	11	5												
45	43	41	39	36	34	31	28	24	21	16	11											
50	48	46	44	42	40	37	35	32	29	25	22	17										
55	53	51	50	48	46	43	41	39	36	33	30	27	23									
60	58	57	55	53	51	49	47	45	43	40	38	35	32	29								
65	63	62	60	59	57	55	53	51	49	47	45	42	40	37	34							
70	68	67	65	64	62	61	60	57	55	53	51	49	47	45	42	39						
75	74	72	71	70	68	66	65	63	61	59	58	56	54	52	49	47	45					
80	79	77	76	75	73	72	70	68	67	65	64	62	60	58	56	54	52	50				
85	84	82	81	80	78	77	75	74	72	71	69	68	66	64	63	61	59	57	55			
90	89	87	86	85	84	82	81	79	78	76	75	73	72	70	68	67	65	63	62	60		
95	94	93	91	90	89	87	86	85	83	82	81	79	78	76	75	73	71	70	68	66	56	
100	99	98	96	95	94	93	91	90	89	87	86	85	83	82	80	79	77	76	74	73	64	53
105	104	103	102	100	99	98	97	95	94	93	91	90	89	87	86	85	83	82	80	79	70	61
110	109	108	107	105	104	103	102	100	99	98	97	95	94	93	91	90	89	87	86	85	77	68

Appendix D: Laws Relating to Gases

Kinetic Energy

All moving objects, by virtue of their motion, are capable of doing work. We call this energy of motion, or *kinetic energy*. The kinetic energy of a moving object is equal to one-half its mass (M) multiplied by its velocity (v) squared. Stated mathematically:

$$\text{Kinetic energy } = \frac{1}{2}\text{Mv}^2$$

Therefore, by doubling the velocity of a moving object, the object's kinetic energy will increase four times.

First Law of Thermodynamics

The first law of thermodynamics is simply the thermal version of the law of conservation of energy, which states that energy cannot be created or destroyed, only transformed from one form to another. Meteorologists use the first law of thermodynamics along with the principles of kinetic energy extensively in analyzing atmospheric phenomena. According to the kinetic theory, the temperature of a gas is proportional to the kinetic energy of the moving molecules. When a gas is heated, its kinetic energy increases because of an increase in molecular motion. Further, when a gas is compressed, the kinetic energy will also be increased and the temperature of the gas will rise. These relationships are expressed in the first law of thermodynamics, as follows: The temperature of a gas may be changed by the addition or subtraction of heat, or by changing the pressure (compression or expansion), or by a combination of both. It is easy to understand how the atmosphere is heated or cooled by the gain or loss of heat. However, when we consider rising and sinking air, the relationships between temperature and pressure become more important. Here an increase in temperature is brought about by performing work on the gas and not by the addition of heat. This phenomenon is called the *adiabatic form* of the first law of thermodynamics.

Boyle's Law

About 1600, the Englishman Robert Boyle showed that if the temperature is kept constant when the pressure exerted on a gas is increased, the volume decreases. This principle, called *Boyle's law,* states: At a constant temperature, the volume of a given mass of gas varies inversely with the pressure. Stated mathematically:

$$P_1V_1 = P_2V_2$$

The symbols P_1 and V_1 refer to the original pressure and volume, respectively, and P_2 and V_2 indicate the new pressure and volume, respectively, after a change occurs. Boyle's law shows that if a given volume of gas is compressed so that the volume is reduced by one-half, the pressure exerted by the gas is doubled. This increase in pressure can be explained by the kinetic theory, which predicts that when the volume of the gas is reduced by one-half, the molecules collide with the walls of the container twice as often. Because density is defined as the mass per unit volume, an increase in pressure results in increased density.

Charles's Law

The relationships between temperature and volume (hence, density) of a gas were recognized about 1787 by the French scientist Jacques Charles, and were stated formally by J. Gay-Lussac in 1802. *Charles's law* states: At a constant pressure, the volume of a given mass is directly proportional to the absolute temperature. In other words, when a quantity of gas is kept at a constant pressure, an increase in temperature results in an increase in volume and vice versa. Stated mathematically:

$$\frac{V_1}{V_2} = \frac{T_1}{T_2}$$

where V_1 and T_1 represent the original volume and temperature, respectively, and V_2 and T_2 represent the final volume and temperature, respectively. This law explains the fact that a gas expands when it is heated. According to the kinetic theory, when heated, particles move more rapidly and therefore collide more often.

The Ideal Gas Law or Equation of State

In describing the atmosphere, three variable quantities must be considered: pressure, temperature, and density (mass per unit volume). The relationships among these variables can be found by combining in a single statement the laws of Boyle and Charles as follows:

$$PV = RT \quad \text{or} \quad P = \rho RT$$

where P is pressure, V volume, R the constant of proportionality, T absolute temperature, and ρ density. This law, called the *ideal gas law*, states:

1. When the volume is kept constant, the pressure of a gas is directly proportional to its absolute temperature.
2. When the temperature is kept constant, the pressure of a gas is proportional to its density and inversely proportional to its volume.
3. When the pressure is kept constant, the absolute temperature of a gas is proportional to its volume and inversely proportional to its density.

Appendix E: Newton's Laws, Pressure-Gradient Force, and Coriolis Force

Newton's Laws of Motion

Because air is composed of atoms and molecules, its motion is governed by the same natural laws that apply to all matter. Simply put, when a force is applied to air, air will be displaced from its original position. Depending on the direction from which the force is applied, the air may move horizontally to produce winds or, in some situations, vertically to generate convective flow. To better understand the forces that produce global winds, it is helpful to become familiar with Newton's first two laws of motion.

Newton's first law of motion states that an object at rest will remain at rest, and an object in motion will continue moving at a uniform speed and in a straight line unless a force is exerted upon it. In simple terms, this law states that objects at rest tend to stay at rest, and objects in motion tend to continue moving at the same rate in the same direction. The tendency of things to resist change in motion (including a change in direction) is known as *inertia*.

You have experienced Newton's first law if you have ever pushed a stalled auto along flat terrain. To start the automobile moving (accelerating) requires a force sufficient to overcome its inertia (resistance to change). However, once this vehicle is moving, a force equal to that of the frictional force between the tires and the pavement is enough to keep it moving.

Moving objects often deviate from straight paths or come to rest, whereas objects at rest begin to move. The changes in motion we observe in daily life are the result of one or more applied forces.

Newton's second law of motion describes the relationship between the forces that are exerted on objects and the observed accelerations that result. Newton's second law states that the acceleration of an object is directly proportional to the net force acting on that body and inversely proportional to the mass of the body. The first part of Newton's second law means that the acceleration of an object changes as the intensity of the applied force changes.

We define *acceleration* as the rate of change in velocity. Because *velocity* describes both the speed and direction of a moving body, velocity can be changed by changing the body's speed, or its direction, or both. Further, the term *acceleration* refers both to decreases and increases in velocity.

For example, we know that when we push down on the gas pedal of an automobile, we experience a positive acceleration (increase in velocity). In contrast, using the brakes retards acceleration (decreases velocity).

In the atmosphere, three forces are responsible for changing the state of motion of winds. These are the pressure-gradient force, the Coriolis force, and friction. From the preceding discussion, it should be clear that the relative strengths of these forces will determine to a large degree the role of each in establishing the flow of air. Further, these forces can be directed in such a way as to increase the speed of airflow, decrease the speed of airflow, or, in many instances, just change the direction of airflow.

Pressure-Gradient Force

The magnitude of the pressure-gradient force is a function of the pressure difference between two points and air density. It can be expressed as

$$F_{\mathrm{PG}} = \frac{1}{\rho} \times \frac{\Delta p}{\Delta n}$$

where:

F_{PG} = pressure-gradient force per unit mass

ρ = density of air

Δp = pressure difference between two points

Δn = distance between two points

Let us consider an example where the pressure 5 kilometers above Little Rock, Arkansas, is 540 millibars, and at 5 kilometers above St. Louis, Missouri, it is 530 millibars. The distance between the two cities is 450 kilometers, and the air density at 5 kilometers is 0.75 kilogram per cubic meter. To use the pressure-gradient equation, we must use compatible units. We must first convert pressure from millibars to pascals, another measure of pressure that has units of (kilograms × meters^{-1} × second^{2}).

In our example, the pressure difference above the two cities is 10 millibars, or 1000 pascals (1000 kg/m·s^{-2}). Thus, we have:

$$F_{\mathrm{PG}} = \frac{1}{0.75} \times \frac{1000}{450,000} = 0.0029 \frac{\mathrm{m}}{\mathrm{s}^2}$$

Newton's second law states that force equals mass times acceleration ($F = m \times a$). In our example, we have considered pressure-gradient force *per unit mass;* therefore, our result is an acceleration ($F/m = a$). Because of the small units shown, pressure-gradient *acceleration* is often expressed as centimeters per second squared. In this example, we have 0.296 cm/s^2.

Coriolis Force as a Function of Wind Speed and Latitude

Figure 6.15 shows how wind speed and latitude conspire to affect the Coriolis force. Consider a west wind at four different latitudes (0°, 20°, 40°, and 60°). After several hours, Earth's rotation has changed the orientation of latitude and longitude of all locations except the equator, such that the wind appears to be deflected to the right. The degree of deflection for a given wind speed increases with latitude because the orientation of latitude and longitude lines changes more at higher latitudes. The degree of deflection of a given latitude increases with wind speed because greater distances are covered in the period of time considered.

We can show mathematically the importance of latitude and wind speed on Coriolis force:

$$F_{\mathrm{CO}} = 2\nu\Omega \sin\phi$$

where:

$$F_{\mathrm{CO}} = \text{Coriolis force } per unit mass of air$$
$$v = \text{wind speed}$$
$$\Omega = \text{Earth's rate of rotation or angular velocity (which is}$$
$$7.29 \times 10^{-5} \text{ radians per second)}$$
$$\phi = \text{latitude}$$

Note that sin ϕ is a trigonometric function equal to zero for an angle of 0° (equator) and 1 when ϕ = 90° (poles).

As an example, the Coriolis force per unit mass that must be considered for a 10-meters-per-second (m/s) wind at 40° is calculated as:

$$
\begin{aligned}
F_{\mathrm{CO}} &= 2\Omega \sin \phi v \\
F_{\mathrm{CO}} &= 2\Omega \sin 40^{\circ} \times 10\,\mathrm{m/s} \\
F_{\mathrm{CO}} &= 2(7.29 \times 10^{-5}\,\mathrm{s}^{-1})\,0.64(10\,\mathrm{m/s}) \\
F_{\mathrm{CO}} &= 0.00094 \text{ meter per second squared} \\
&= 0.094 \text{ cm s}^{-2}
\end{aligned}
$$

The result (0.094 cm/s^{-2}) is expressed as an acceleration because we are considering force per unit mass and Force = Mass × Acceleration.

Using this equation, one could calculate the Coriolis force for any latitude or wind speed. Consider Table E.1, which shows the Coriolis force per unit mass for three specific wind speeds at various latitudes. All values are expressed in centimeters per second squared (cm/s^{-2}). Because pressure-gradient force and Coriolis force approximately balance under geostrophic conditions, we can see from our table that the pressure-gradient force (per unit mass) of 0.296 cm/s^{-2} illustrated in the preceding discussion of pressure-gradient force would produce relatively strong winds.

Table E.1 Coriolis Force for Three Wind Speeds at Various Latitudes

Wind Speed		Latitude (ϕ)			
		0°	20°	40°	60°
(m/s)	(kph)	Coriolis Force (cm/s^2)			
5	18	0	0.025	0.047	0.063
10	36	0	0.050	0.094	0.126
25	90	0	0.125	0.235	0.316

Appendix F: Saffir–Simpson Hurricane Wind Scale

Scale Number (category)		Wind Speed (mph)	Typical Central Pressure (millibars)	Typical Storm Surge (meters)	Typical Storm Surge (feet)	Damage
1	119–153	74–95	≥ 980	1.2–1.5	4–5	*Minimal.* No real damage to building structures. Damage primarily to unanchored mobile homes, shrubbery, and trees. Also, some coastal-road flooding and minor pier damage.
2	154–177	96–110	965–979	1.6–2.4	6–8	*Moderate.* Some roofing material, door, and window damage to buildings. Some trees blown down. Considerable damage to mobile homes. Coastal and low-lying escape routes flood 2 to 4 hours before arrival of the hurricane center. Small craft in unprotected anchorages break moorings.
3	178–208	111–129	945–964	2.5–3.6	9–12	*Extensive.* Some structural damage to small residences and utility buildings. Large trees blown down. Mobile homes are destroyed. Flooding near the coast destroys smaller structures; larger structures damaged due to battering by floating debris. Terrain lower than 2 meters above sea level may be flooded inland 13 km or more. Evacuation of low-lying residences within several blocks of the shoreline may be required.
4	209–251	130–156	920–944	3.7–5.4	13–18	*Extreme.* Some complete roof structure failures on small residences. Extensive damage to doors and windows. Low-lying escape routes may be cut off by rising water 3 to 5 hours before arrival of the hurricane center. Major damage to lower floors of structures near the shore. Terrain lower than 3 meters above sea level may be flooded, requiring massive evacuation of residential areas as far inland as 10 km.
5	>252	>157	<920	>5.4	>18	*Catastrophic.* Complete roof failure on many residences and industrial buildings. Some complete building failures. Severe window and door damage. Low-lying escape routes are cut off by rising water 3 to 5 hours before arrival of the hurricane center. Major damage to lower floors of all structures located less than 5 meters above sea level and within 500 meters of the shoreline. Massive evacuation of residential areas on low ground within 8 to 16 km of the shoreline may be required.

Appendix G: Climate Data

Table G.1 includes data for 51 stations around the world that represent many different climate types. Temperatures are given in degrees Celsius and precipitation in millimeters. Names and locations are given in Table G.2, along with the elevation (in meters) of each station and its Köppen classification. This format was used so that you can use the data in exercises to reinforce your understanding of climate controls and climate classification.

Table G.1 Selected Climate Data for the World (Temperature °F/Precipitation mm)

	J	F	M	A	M	J	J	A	S	O	N	D	YR.
1	1.7	4.4	7.9	13.2	18.4	23.8	25.8	24.8	21.4	14.7	6.7	2.8	13.8
	10	10	13	13	20	15	30	32	23	18	10	13	207
2	−10.4	−8.3	−4.6	3.4	9.4	12.8	16.6	14.9	10.8	5.5	−2.3	−6.4	3.5
	18	25	25	30	51	89	64	71	33	20	18	15	459
3	10.2	10.8	13.7	17.9	22.2	25.7	26.7	26.5	24.2	19.0	13.3	10.0	18.4
	66	84	99	74	91	127	196	168	147	71	53	71	1247
4	−23.9	−17.5	−12.5	−2.7	8.4	14.8	15.6	12.8	6.4	−3.1	−15.8	−21.9	−3.3
	23	13	18	8	15	33	48	53	33	20	18	15	297
5	−17.8	−15.3	−9.2	−4.4	4.7	10.9	16.4	14.4	10.3	3.3	−3.6	−12.8	−0.3
	58	58	61	48	53	61	81	71	58	61	64	64	738
6	−8.2	−7.1	−2.4	5.4	11.2	14.7	18.9	17.4	12.7	7.4	−0.4	−4.6	5.4
	21	23	29	35	52	74	39	40	35	29	26	21	424
7	12.8	13.9	15.0	15.0	17.8	20.0	21.1	22.8	22.2	18.3	17.2	15.0	17.6
	69	74	46	28	3	3	0	0	5	10	28	61	327
8	18.9	20.0	21.1	22.8	25.0	26.7	27.2	27.8	27.2	25.0	21.1	20.0	23.6
	51	48	58	99	163	188	172	178	241	208	71	43	1520
9	−4.4	−2.2	4.4	10.6	16.7	21.7	23.9	22.7	18.3	11.7	3.8	−2.2	10.4
	46	51	69	84	99	97	97	81	97	61	61	51	894
10	−5.6	−4.4	0.0	6.1	11.7	16.7	20.0	18.9	15.5	10.0	3.3	−2.2	7.5
	112	96	109	94	86	81	74	61	89	81	107	99	1089
11	−2.1	0.9	4.7	9.9	14.7	19.4	24.7	23.6	18.3	11.5	3.4	−0.2	10.7
	34	30	40	45	36	25	15	22	13	29	33	31	353
12	12.8	13.9	15.0	16.1	17.2	18.8	19.4	22.2	21.1	18.8	16.1	13.9	15.9
	53	56	41	20	5	0	0	2	5	13	23	51	269
13	−0.1	1.8	6.2	13.0	18.7	24.2	26.4	25.4	21.1	14.9	6.7	1.6	13.3
	50	52	78	94	95	109	84	77	70	73	65	50	897
14	2.7	3.2	7.1	13.2	18.8	23.4	25.7	24.7	20.9	15.0	8.7	3.4	13.9
	77	63	82	80	105	82	105	124	97	78	72	71	1036
15	12.8	15.0	18.9	21.1	26.1	31.1	32.7	33.9	31.1	22.2	17.7	13.9	23.0
	10	9	6	2	0	0	6	13	10	10	3	8	77
16	25.6	25.6	24.4	25.0	24.4	23.3	23.3	24.4	24.4	25.0	25.6	25.6	24.7
	259	249	310	165	254	188	168	117	221	183	213	292	2619
17	25.9	25.8	25.8	25.9	26.4	26.6	26.9	27.5	27.9	27.7	27.3	26.7	26.7
	365	326	383	404	185	132	68	43	96	99	189	143	2433
18	13.3	13.3	13.3	13.3	13.9	13.3	13.3	13.3	13.9	13.3	13.3	13.9	13.5
	99	112	142	175	137	43	20	30	69	112	97	79	1115
19	25.9	26.1	25.2	23.9	22.3	21.3	20.8	21.1	21.5	22.3	23.1	24.4	23.2
	137	137	143	116	73	43	43	43	53	74	97	127	1086
20	13.8	13.5	11.4	8.0	3.7	1.2	1.4	2.9	5.5	9.2	11.4	12.9	7.9
	21	16	18	13	25	15	15	17	12	7	15	18	171
21	1.5	1.3	3.1	5.8	10.2	12.6	15.0	14.7	12.0	8.3	5.5	3.3	7.8
	179	139	109	140	83	126	141	167	228	236	207	203	1958
22	−0.5	0.2	3.9	9.0	14.3	17.7	19.4	18.8	15.0	9.6	4.7	1.2	9.5
	41	37	30	39	44	60	67	65	45	45	44	39	556

(Continued)

TABLE G.1 *(Continued)*

	J	F	M	A	M	J	J	A	S	O	N	D	YR.
23	6.1	5.8	7.8	9.2	11.6	14.4	15.6	16.0	14.7	12.0	9.0	7.0	10.8
	133	96	83	69	68	56	62	80	87	104	138	150	1126
24	10.8	11.6	13.6	15.6	17.2	20.1	22.2	22.5	21.2	18.2	14.4	11.5	16.6
	111	76	109	54	44	16	3	4	33	62	93	103	708
25	−9.9	−9.5	−4.2	4.7	11.9	16.8	19.0	17.1	11.2	4.5	−1.9	−6.8	4.4
	31	28	33	35	52	67	74	74	58	51	36	36	575
26	8.0	9.0	10.9	13.7	17.5	21.6	24.4	24.2	21.5	17.2	12.7	9.5	15.9
	83	73	52	50	48	18	9	18	70	110	113	105	749
27	−9.0	−9.0	−6.6	−4.1	0.4	3.6	5.6	5.5	3.5	−0.6	−4.5	−7.6	−1.9
	202	180	164	166	197	249	302	278	208	183	190	169	2488
28	−2.9	−3.1	−0.7	4.4	10.1	14.9	17.8	16.6	12.2	7.1	2.8	0.1	6.6
	43	30	26	31	34	45	61	76	60	48	53	48	555
29	12.8	13.9	17.2	18.9	22.2	23.9	25.5	26.1	25.5	23.9	18.9	15.0	20.3
	66	41	20	5	3	0	0	0	3	18	46	66	268
30	24.6	24.9	25.0	24.9	25.0	24.2	23.7	23.8	23.9	24.2	24.2	24.7	24.4
	81	102	155	140	133	119	99	109	206	213	196	122	1675
31	21.1	20.4	20.9	21.7	23.0	26.0	27.3	27.3	27.5	27.5	26.0	25.2	24.3
	0	2	0	0	1	15	88	249	163	49	5	6	578
32	20.4	22.7	27.0	30.6	33.8	34.2	33.6	32.7	32.6	30.5	25.5	21.3	28.7
	0	0	0	0	0	2	1	11	2	0	0	0	16
33	17.8	18.1	18.8	18.8	17.8	16.2	14.9	15.5	16.8	18.6	18.3	17.8	17.5
	46	51	102	206	160	46	18	25	25	53	109	81	922
34	20.6	20.7	19.9	19.2	16.7	13.9	13.9	16.3	19.1	21.8	21.4	20.9	18.7
	236	168	86	46	13	8	0	3	8	38	94	201	901
35	11.7	13.3	16.7	18.6	19.2	20.0	20.3	20.5	20.5	19.1	15.9	12.9	17.4
	20	41	179	605	1705	2875	2455	1827	1231	447	47	5	11437
36	26.2	26.3	27.1	27.2	27.3	27.0	26.7	27.0	27.4	27.4	26.9	26.6	26.9
	335	241	201	141	116	97	61	50	78	91	151	193	1755
37	−0.8	2.6	5.3	8.5	13.1	17.0	17.2	17.3	15.3	11.5	5.7	0.3	9.4
	0	0	1	1	18	72	157	151	68	4	1	0	473
38	24.5	25.8	27.9	30.5	32.7	32.5	30.7	30.1	29.7	28.1	25.9	24.6	28.6
	24	7	15	25	52	53	83	124	118	267	308	157	1233
39	−18.7	−18.1	−16.7	−11.7	−5.0	0.6	5.3	5.8	1.4	−4.2	−12.3	−15.8	−7.5
	8	8	8	8	15	20	36	43	43	33	13	12	247
40	−21.9	−18.6	−12.5	−5.0	9.7	15.6	18.3	16.1	10.3	0.8	−10.6	−18.4	−1.4
	15	8	8	13	30	51	51	51	28	25	18	20	318
41	−4.7	−1.9	4.8	13.7	20.1	24.7	26.1	24.9	19.9	12.8	3.8	−2.7	11.8
	4	5	8	17	35	78	243	141	58	16	10	3	623
42	24.3	25.2	27.2	29.8	29.5	27.8	27.6	27.1	27.6	28.3	27.7	25.0	27.3
	8	5	6	17	260	524	492	574	398	208	34	3	2530
43	25.8	26.3	27.8	28.8	28.2	27.4	27.1	27.1	26.7	26.5	26.1	25.7	27.0
	6	13	12	65	196	285	242	277	292	259	122	37	1808
44	3.7	4.3	7.6	13.1	17.6	21.1	25.1	26.4	22.8	16.7	11.3	6.1	14.7
	48	73	101	135	131	182	146	147	217	220	101	60	1563

(Continued)

TABLE G.1 *(Continued)*

	J	F	M	A	M	J	J	A	S	O	N	D	YR.
45	−15.8	−13.6	−4.0	8.5	17.7	21.5	23.9	21.9	16.7	6.1	−6.2	−13.0	5.3
	8	15	15	33	25	33	16	35	15	47	22	11	276
46	−46.8	−43.1	−30.2	−13.5	2.7	12.9	15.7	11.4	2.7	−14.3	−35.7	−44.5	−15.2
	7	5	5	4	5	25	33	30	13	11	10	7	155
47	19.2	19.6	18.4	16.4	13.8	11.8	10.8	11.3	12.6	16.3	15.9	17.7	15.2
	84	104	71	109	122	140	140	109	97	106	81	79	1242
48	28.2	27.9	28.3	28.2	26.8	25.4	25.1	25.8	27.7	29.1	29.2	28.7	27.6
	341	338	274	121	9	1	2	5	17	66	156	233	1562
49	21.9	21.9	21.2	18.3	15.7	13.1	12.3	13.4	15.3	17.6	19.4	21.0	17.6
	104	125	129	101	115	141	94	83	72	80	77	86	1205
50	−7.2	−7.2	−4.4	−0.6	4.4	8.3	10.0	8.3	5.0	1.1	−3.3	−6.1	0.7
	84	66	86	62	89	81	79	94	150	145	117	79	1132
51	−4.4	−8.9	−15.5	−22.8	−23.9	−24.4	−26.1	−26.1	−24.4	−18.8	−10.0	−3.9	−17.4
	13	18	10	10	10	8	5	8	10	5	5	8	110

Table G.2 Locations and Climate Classifications for Table G.1

Station No.	City	Location	Elevation (m)	Köppen Classification
		North America		
1	Albuquerque, N.M.	lat. 35°05′N	1593	BWk
		long. 106°40′W		
2	Calgary, Canada	lat. 51°03′N	1062	Dfb
		long. 114°05′W		
3	Charleston, S.C.	lat. 32°47′N	18	Cfa
		long. 79°56′W		
4	Fairbanks, Alaska	lat. 64°50′N	134	Dfc
		long. 147°48′W		
5	Goose Bay, Canada	lat. 53°19′N	45	Dfb
		long. 60°33′W		
6	Lethbridge, Canada	lat. 49°40′N	920	Dfb
		long. 112°39′W		
7	Los Angeles, Calif.	lat. 34°00′N	29	BSk
		long. 118°15′W		
8	Miami, Fla.	lat. 25°45′N	2	Am
		long. 80°11′W		
9	Peoria, III.	lat. 40°45′N	180	Dfa
		long. 89°35′W		
10	Portland, Me.	lat. 43°40′N	14	Dfb
		long. 70°16′W		
11	Salt Lake City, Utah	lat. 40°46′N	1288	BSk
		long. 111°52′W		
12	San Diego, Calif.	lat. 32°43′N	26	BSk
		long. 117°10′W		
13	St. Louis, Mo.	lat. 38°39′N	172	Cfa
		long. 90°15′W		
14	Washington, D.C.	lat. 38°50′N	20	Cfa
		long. 77°00′W		
15	Yuma, Ariz.	lat. 32°40′N	62	BWh
		long. 114°40′W		
		South America		
16	Iquitos, Peru	lat. 3°39′S	115	Af
		long. 73°18′W		
17	Manaus, Brazil	lat. 3°01′S	60	Am
		long. 60°00′W		
18	Quito, Ecuador	lat. 0°17′S	2766	Cfb
		long. 78°32′W		
19	Rio de Janeiro, Brazil	lat. 22°50′S	26	Aw
		long. 43°20′W		
20	Santa Cruz, Argentina	lat. 50°01′S	111	BSk
		long. 60°30′W		
		Europe		
21	Bergen, Norway	lat. 60°24′N	44	Cfb
		long. 5°20′E		
22	Berlin, Germany	lat. 52°28′N	50	Cfb
		long. 13°26′E		
23	Brest, France	lat. 48°24′N	103	Cfb
		long. 4°30′W		
24	Lisbon, Portugal	lat. 38°43′N	93	Csa
		long. 9°05′W		
25	Moscow, Russia	lat. 55°45′N	156	Dfb
		long. 37°37′E		
26	Rome, Italy	lat. 41°52′N	3	Csa
		long. 12°37′E		
27	Santis, Switzerland	lat. 47°15′N	2496	ET
		long. 9°21′E		
28	Stockholm, Sweden	lat. 59°21′N	52	Dfb
		long. 18°00′E		
		Africa		
29	Benghazi, Libya	lat. 32°06′N	25	BSh
		long. 20°06′E		
30	Coquilhatville, Zaire	lat. 0°01′N	21	Af
		long. 18°17′E		
31	Dakar, Senegal	lat. 14°40′N	23	BSh
		long. 17°28′W		
32	Faya, Chad	lat. 18°00′N	251	BWh
		long. 21°18′E		
33	Nairobi, Kenya	lat. 1°16′S	1791	Csb
		long. 36°47′E		
34	Harare, Zimbabwe	lat. 17°50′S	1449	Cwb
		long. 30°52′E		

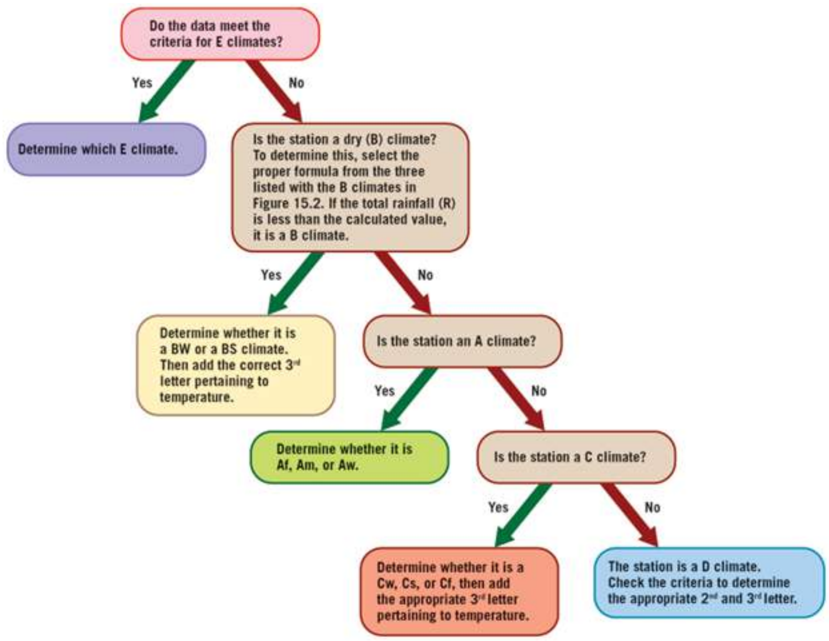
(Continued)

TABLE G.2 (*Continued*)

Station No.	City	Location	Elevation (m)	Köppen Classification
		Asia		
35	Cherrapunji, India	lat. 25°15′N	1313	Cwb
		long. 91°44′E		
36	Djakarta, Indonesia	lat. 6°11′S	8	Am
		long. 106°45′E		
37	Lhasa, Tibet	lat. 29°40′N	3685	Cwb
		long. 91°07′E		
38	Madras, India	lat. 13°00′N	16	Aw
		long. 80°11′E		
39	Novaya Zemlya, Russia	lat. 72°23′N	15	ET
		long. 54°46′E		
40	Omsk, Russia	lat. 54°48′N	85	Dfb
		long. 73°19′E		
41	Beijing, China	lat. 39°57′N	52	Dwa
		long. 116°23′E		
42	Rangoon, Myanmar	lat. 16°46′N	23	Am
		long. 96°10′E		
43	Ho Chi Minh City, Viet Nam	lat. 10°49′N	10	Aw
		long. 106°40′E		
44	Tokyo, Japan	lat. 35°41′N	6	Cfa
		long. 139°46′E		
45	Urumchi, China	lat. 43°47′N	912	Dfa
		long. 87°43′E		
46	Verkhoyansk, Russia	lat. 67°33′N	137	Dfd
		long. 133°23′E		
		Australia and New Zealand		
47	Auckland, New Zealand	lat. 37°43′S	49	Csb
		long. 174°53′E		
48	Darwin, Australia	lat. 12°26′S	27	Aw
		long. 131°00′E		
49	Sydney, Australia	lat. 33°52′S	42	Cfb
		long. 151° 179E		
		Greenland		
50	Ivigtut, Greenland	lat. 61°12′N	29	ET
		long. 48° 109W		
		Antarctica		
51	McMurdo Station, Antarctica	lat. 77°53′S	2	EF
		long. 167°00′E		

Use Figure 15.2 to determine the proper Köppen classification. The flowchart in Figure G.1 will help guide you through the classification process. Once you have classified a station, determine a likely location, based on factors such as mean annual temperature, annual temperature range, total precipitation, and seasonal precipitation distribution. Your location need not be a specific city; it could be a description of the station's setting, such as "middle-latitude continental" or "subtropical with a strong monsoon influence." It would also be a good idea to list the reasons for your selection. You may check your answer by examining the list of stations in Table G.2.

Figure G.1 Classifying Climates Using Figure 15.2



If you simply wish to examine the data for a specific place or data for a specific climate type, consult the list in Table G.2.

Glossary

Absolute humidity

The mass of water vapor per volume of air (usually expressed as grams of water vapor per cubic meter of air).

Absolute instability

The condition of air that has an environmental lapse rate that is greater than the dry adiabatic rate (1°C per 100 meters).

Absolute stability

The condition of air that has an environmental lapse rate that is less than the wet adiabatic rate.

Absolute zero

The zero point on the Kelvin temperature scale, representing the temperature at which all molecular motion is presumed to cease.

Absorptivity

A measure of the amount of radiant energy absorbed by a substance.

Acid precipitation

Rain or snow with a pH value that is less than the value for uncontaminated rain.

Adiabatic temperature change

The cooling or warming of air caused when air expands or is compressed, not because heat is added or subtracted.

Advanced Weather Interactive Processing System (AWIPS)

An information processing, display, and communication system used by weather forecasters that integrates all model and observational data, including satellite and radar data, in one location.

Advection

Horizontal convective motion, such as wind.

Advection fog

Fog formed when warm moist air is blown over a cool surface and chilled below the dew point.

Aerosols

Tiny solid and liquid particles suspended in the atmosphere.

Aerovane

A device that resembles a wind vane with a propeller at one end. Used to indicate wind speed and direction.

Air

A mixture of many discrete gases, of which nitrogen and oxygen are most abundant, in which varying quantities of tiny solid and liquid particles are suspended.

Air mass

A large body of air, usually 1600 kilometers or more across, that is characterized by homogeneous physical properties at any given altitude.

Air-mass thunderstorm

See Ordinary cell thunderstorm.

Air-mass weather

The conditions experienced in an area as an air mass passes over it. Because air masses are large and relatively homogeneous, air-mass weather will be fairly constant and may last for several days.

Air pollutants

Airborne particles and gases occurring in concentrations that endanger the health and well-being of organisms or disrupt the orderly functioning of the environment.

Air pressure

See Atmospheric pressure.

Air Quality Index (AQI)

A standardized indicator for reporting daily air quality to the general public. It is calculated for five major pollutants regulated by the Clean Air Act.

Albedo

The reflectivity of a substance, usually expressed as a percentage of the incident radiation reflected.

Aleutian low

A large cell of low pressure centered over the Aleutian Islands of the North Pacific during the winter.

Altimeter

An aneroid barometer calibrated to indicate altitude instead of pressure.

Altitude (of the Sun)

The angle of the Sun above the horizon.

Altocumulus

Middle-level clouds that are white to gray, often made up of separate globules.

Altostratus

A middle-level stratified veil of clouds that is generally thin and may produce very light precipitation.

Analog method

A statistical approach to weather forecasting in which current conditions are matched with records of similar past weather events with the idea that the succession of events in the past will be paralleled by current conditions.

Anemometer

An instrument used to determine wind speed.

Aneroid barometer

An instrument for measuring air pressure; it consists of evacuated metal chambers that are very sensitive to variations in air pressure.

Annual energy budget

The annual balance of incoming and outgoing radiation, as well as the energy balance that exists between Earth's surface and its atmosphere.

Annual mean temperature

An average of the 12 monthly means.

Annual temperature range

The difference between the warmest and coldest monthly means.

Antarctic Circle

The parallel of latitude, 66½° south latitude, marking the northernmost location where the midnight Sun is visible on the southern summer solstice.

Anticyclone

An area of high atmospheric pressure characterized by diverging and rotating winds and subsiding air aloft.

Anticyclonic flow

Winds blow out and flow clockwise about an anticyclone (high) in the Northern Hemisphere, and they blow out and flow counterclockwise about an anticyclone in the Southern Hemisphere.

Aphelion

The point in the orbit of a planet that is farthest from the Sun.

Apparent temperature

The air temperature perceived by a person.

Arctic (A) air mass

A bitterly cold air mass that forms over the frozen Arctic Ocean.

Arctic Circle

The parallel of latitude, 66½° north latitude, marking the southernmost location where the midnight sun is visible on the northern summer solstice.

Arctic sea smoke

A dense and often extensive steam fog occurring over high-latitude ocean areas in winter.

Arid

See Desert.

Atmosphere

The gaseous portion of a planet, the planet's envelope of air; one of the traditional subdivisions of Earth's physical environment.

Atmospheric pressure

The force exerted by the weight of a column of air above a given point.

Atmospheric river

Narrow zones in the atmosphere that transport significant amounts of moisture to regions outside the tropics.

Atmospheric sounding

The plot of weather data collected by a radiosonde.

Atmospheric window

Terrestrial radiation between 8 and 11 micrometers in length to which the troposphere is transparent.

Aurora

A bright and ever-changing display of light caused by solar radiation interacting with the upper atmosphere in the region of the poles. It is called *aurora borealis* in the Northern Hemisphere and *aurora australis* in the Southern Hemisphere.

Automated Surface Observing System (ASOS)

A widely used, standardized set of automated weather instruments that provide routine surface observations.

Autumnal equinox

See Equinox.

Azores high

See Bermuda-Azores high.

Backdoor cold front

A cold front moving toward the west or southwest along the Atlantic Seaboard.

Barometric pressure

Atmospheric pressure measured using a barometer.

Bergeron process

A theory that relates the formation of precipitation to supercooled clouds, freezing nuclei, and the different saturation levels of ice and liquid water.

Bermuda/Azores high

The name given to the subtropical high in the North Atlantic centered near the island of Bermuda during the summer and migrating toward the Azores in the eastern North Atlantic during the winter.

Bimetal strip

A thermometer consisting of two thin strips of metal welded together, which have widely different coefficients of thermal expansion. When temperature changes, the two metals expand or contract unequally and cause changes in the curvature of the element. Commonly used in thermographs.

Biosphere

The totality of life-forms on Earth.

Black carbon

An air pollutant, such as soot, that is caused by incomplete combustion.

Blizzard

A violent and extremely cold wind, laden with dry snow picked up from the ground.

Blocking high

Airflow pattern created by stagnant anticyclones which block or redirect the migration of midlatitude cyclones.

Bora

In the region of the eastern shore of the Adriatic Sea, a cold, dry northeasterly wind that blows down from the mountains.

Boundary layer

The layer of atmosphere closest to Earth that is directly influenced by the daily cycle of the Sun.

Buys Ballot's law

A law which states that with your back to the wind in the Northern Hemisphere, low pressure will be to your left and high pressure to your right. The reverse is true in the Southern Hemisphere.

Calorie

The amount of heat required to raise the temperature of 1 gram of water 1°C.

Canadian Meteorological Centre

The office in Canada responsible for making predictions about the future state of the atmosphere.

Celsius scale

A temperature scale (at one time called the centigrade scale) devised by Anders Celsius in 1742 and used where the metric system is in use. For water at sea level, 0° is designated the ice point and 100° the steam point.

Chinook

The name applied to a foehn wind in the Rocky Mountains.

Circle of illumination

The line (great circle) separating daylight from darkness on Earth.

Cirrocumulus

High, thin, ice-crystal clouds that form ripples or waves, or globular masses in rows.

Cirrostratus

A high thin sheet of ice-crystal clouds that may give the sky a milky look and sometimes form optical effects, such as halos, sundogs, and sun pillars.

Cirrus

One of three basic cloud forms; also one of the three high cloud types. They are thin, delicate ice-crystal clouds often appearing as veil-like patches or thin, wispy fibers.

Climate

A description of aggregate weather conditions; the sum of all statistical weather information that helps describe a place or region.

Climate change

A study dealing with variations in climate on many different time scales from decades to millions of years, and the possible causes of such variations.

Climate Prediction Center (CPC)

The office responsible for creating long-term forecasts.

Climate system

The exchanges of energy and moisture occurring among the atmosphere, hydrosphere, lithosphere, biosphere, and cryosphere.

Climatological forecasting

A relatively simple way of generating forecasts using climatological data.

Cloud

A form of condensation best described as a dense concentration of suspended water droplets or tiny ice crystals.

Cloud condensation nuclei

Microscopic particles that serve as surfaces on which water vapor condenses.

Cloud seeding

The introduction into clouds of particles (most commonly dry ice or silver iodide) for the purpose of altering the cloud's natural development.

Clouds of vertical development

A cloud that has its base in the low height range and extends upward into the middle or high altitudes.

Cloud-to-ground lightning

A type of lightning in which the electrical discharge occurs between the cloud and Earth's surface.

Cold conveyor belt

Airflow in a midlatitude cyclone that starts at the surface ahead (poleward) of the warm front and flows westward toward the center of the cyclone.

Cold front

The discontinuity at the forward edge of an advancing cold air mass that is displacing warmer air in its path.

Cold-type occluded front

A front that forms when the air behind the cold front is colder than the air underlying the warm front it is overtaking.

Collision–coalescence process

A theory of raindrop formation in warm clouds (above 0°C) in which large cloud droplets (“giants”) collide and join together with smaller droplets to form a raindrop. Opposite electrical charges may bind the cloud droplets together.

Condensation

The change of state from a gas to a liquid.

Conditional instability

The condition of moist air with an environmental lapse rate between the dry and wet adiabatic rates.

Conduction

The transfer of heat through matter by molecular activity. Energy is transferred during collisions among molecules.

Conservation of angular momentum, law of

The product of the velocity of an object around a center of rotation (axis) and the distance of the object from the axis is constant.

Constant-pressure surface

A surface along which the atmospheric pressure is everywhere equal at any given moment.

Continental (c) air mass

An air mass that forms over land; it is normally relatively dry.

Continental climate

A climate lacking marine influence and characterized by more extreme temperatures than in marine climates; therefore, it has a relatively high annual temperature range for its latitude.

Contrail

A cloudlike streamer frequently observed behind aircraft flying in clear, cold, and humid air and caused by the addition to the atmosphere of water vapor from engine exhaust gases.

Controls of temperature

See Temperature controls.

Convection

The transfer of heat by the movement of a mass or substance. It can take place only in fluids.

Convection cell

Circulation that results from the uneven heating of a fluid; the warmer parts of the fluid expand and rise because of their buoyancy, and the cooler parts sink.

Convergence

The condition that exists when the wind distribution within a given region results in a net horizontal inflow of air into the area. Because convergence at lower levels is associated with an upward movement of air, areas of convergent winds are regions favorable to cloud formation and precipitation.

Conveyor belt model

A modern view of cyclogenesis that provides a description of the three-dimensional airflow within a midlatitude cyclone.

Cooling degree-day

Each degree of temperature of the daily mean above 65°F. The amount of energy required to maintain a certain temperature in a building is proportional to the cooling degree-days total.

Coriolis force

The deflective effect of Earth's rotation on all free-moving objects, including the atmosphere and oceans. Deflection is to the right in the Northern Hemisphere and to the left in the Southern Hemisphere.

Corona

A bright, whitish disk centered on the Moon or Sun that results from diffraction when the objects are veiled by a thin cloud layer.

Country breeze

A circulation pattern characterized by a light wind blowing into a city from the surrounding countryside. It is best developed on clear and otherwise calm nights when the urban heat island is most pronounced.

Cryosphere

Collective term for the ice and snow that exist on Earth. One of the *spheres* of the climate system.

Cumulonimbus

A towering thunderstorm cloud associated with heavy rainfall, thunder, lightning, hail, and tornadoes.

Cumulus

One of three basic cloud forms; also the name of one of the clouds of vertical development. Cumulus are billowy, individual cloud masses that often have flat bases.

Cumulus stage

The initial stage in thunderstorm development, in which the growing cumulonimbus is dominated by strong updrafts.

Cup anemometer

See Anemometer.

Cut-off low

A blocking pattern created by low-pressure systems that are disconnected from the steering winds of the jet stream.

Cyclogenesis

The process that creates or develops a new cyclone; also the process that produces an intensification of a preexisting cyclone.

Cyclone

An area of low atmospheric pressure characterized by rotating and converging winds and ascending air.

Cyclonic flow

Winds blowing in and counterclockwise about a cyclone (low) in the Northern Hemisphere and in and clockwise about a cyclone in the Southern Hemisphere.

Daily mean temperature

The mean temperature for a day that is determined by averaging the hourly readings or, more commonly, by averaging the maximum and minimum temperatures for a day.

Daily temperature range

The difference between the maximum and minimum temperatures for a day.

Dart leader

See Leader.

Dendrochronology

The dating and study of annual tree rings.

Deposition

The process whereby water vapor changes directly to ice, without going through the liquid state.

Desert

One of the two types of dry climate—the driest of the dry climates.

Dew

A form of condensation consisting of small water drops on grass or other objects near the ground that forms when the surface temperature drops below the dew point. Usually associated with radiation cooling on clear, calm nights.

Dew point

The temperature to which air must be cooled in order to reach saturation.

Diffraction

The interference of any type of wave as it passes near an obstacle comparable in size to its wavelength.

Diffused light

Solar energy is scattered and reflected in the atmosphere and reaches Earth's surface in the form of diffuse blue light from the sky.

Dispersion

The separation of colors by refraction.

Dissipating stage

The final stage of a thunderstorm that is dominated by downdrafts and entrainment leading to the evaporation of the cloud structure.

Diurnal

Daily, especially pertaining to actions that are completed within 24 hours and that recur every 24 hours.

Divergence

The condition that exists when the distribution of winds within a given area results in a net horizontal outflow of air from the region. In divergence at lower levels, the resulting deficit is compensated for by a downward movement of air from aloft; hence, areas of divergent winds are unfavorable to cloud formation and precipitation.

Doldrums

The equatorial belt of calms or light variable winds lying between the two trade wind belts.

Doppler radar

A type of radar that has the capacity of detecting motion directly.

Dropsonde

A weather instrument that is dropped from an airplane to measure atmospheric conditions from the height of the plane to the ground.

Drizzle

Precipitation from stratus clouds consisting of tiny droplets.

Dry adiabatic rate

The rate of adiabatic cooling or warming in unsaturated air. The rate of temperature change is 1°C per 100 meters.

Dry climate

A climate in which yearly precipitation is not as great as the potential loss of water by evaporation.

Dry conveyer belt

Airflow in a midlatitude cyclone that starts in the uppermost troposphere and splits. One branch descends behind the cold front, while the other wraps around the low to form a dry slot.

Dryline

A narrow zone in the atmosphere along which there is an abrupt change in moisture as when dry continental tropical air converges with humid maritime tropical air. The denser cT air acts to lift the less dense mT air, producing clouds and storms.

Dry-summer subtropical climate

See Mediterranean climate.

Dual-polarization technology

New radar technology that sends and receives both vertical and horizontal pulses of energy to provide more precise information to weather forecasters about the type of precipitation and its intensity, size, and location.

Earth system

The complex and continuously interacting system consisting of the living and nonliving components of Earth, powered by the Sun's energy and Earth's internal heat.

Easterly wave

A large migratory wavelike disturbance in the trade winds that sometimes triggers the formation of a hurricane.

Eccentricity

The variation of an ellipse from a circle.

Electromagnetic radiation

See Radiation.

El Niño

The name given to the periodic warming of the ocean that occurs in the central and eastern Pacific. A major El Niño episode can cause extreme weather in many parts of the world. The opposite of *La Niña*.

Energy

The capacity to do work, such as making an object move.

Enhanced Fujita Scale (EF Scale)

A scale developed by T. Theodore Fujita for classifying the severity of a tornado, based on the correlation of wind speed with the degree of destruction. The Enhanced Fujita Scale is an update to the original Fujita Scale to more accurately depict wind speeds based on damage.

Ensemble forecasting

A forecasting technique that involves running a weather forecast model many times with slightly different initial conditions to determine forecast uncertainty.

Entrainment

The infiltration of surrounding air into a vertically moving air column. For example, the influx of cool, dry air into the downdraft of a cumulonimbus cloud; a process that acts to intensify the downdraft.

Environmental lapse rate

The rate of temperature decrease with height in the troposphere.

Equatorial low

A quasi-continuous belt of low pressure lying near the equator and between the subtropical highs.

Equilibrium level

The height of a rising air parcel at which the parcel becomes colder than the surrounding environment after the level of free convection.

Equinox

The point in time when the vertical rays of the Sun are striking the equator. In the Northern Hemisphere, March 20 or 21 is the *vernal*, or *spring*, *equinox*, and September 22 or 23 is the *autumnal equinox*. Lengths of daylight and darkness are equal at all latitudes at equinox.

Evaporation

The process by which a liquid is transformed into gas.

Eye

A roughly circular area of relatively light winds and fair weather at the center of a hurricane.

Eye wall

The doughnut-shaped area of intensive cumulonimbus development and very strong winds that surrounds the eye of a hurricane.

Fahrenheit scale

A temperature scale devised by Gabriel Daniel Fahrenheit in 1714 and used in the English system. For water at sea level, 32° is designated the ice point and 212° the steam point.

Fallstreaks

Precipitation falling from clouds that evaporates before it reaches the ground, also called virga.

Fall wind

See Katabatic wind.

Feedback mechanisms

Several different possible outcomes that may result when one of the atmospheric system's elements is altered.

Ferrel cell

The middle cell in the three-cell global circulation model; named for William Ferrel.

Flash

The total discharge of lightning, which is usually perceived as a single flash of light but which actually consists of several flashes. *See also* Stroke.

Foehn

A warm, dry wind on the lee side of a mountain range that owes its relatively high temperature largely to adiabatic heating during descent down mountain slopes.

Fog

A cloud with its base at or very near Earth's surface.

Forecast model

Complex computer programs used to make numerical weather predictions.

Forecast skill

An index of the degree of accuracy of a set of forecasts as compared to forecasts based on some standard, such as chance or climatic data.

Freezing

The change of state from liquid to solid.

Freezing nucleus

Solid particle that has a crystal form resembling that of ice; it serves as a core for the formation of ice crystals.

Freezing rain

A coating of ice on objects formed when supercooled rain freezes on contact. A storm that produces glaze is termed an "icing storm."

Friction

A force that acts to slow moving objects and decrease wind speed.

Front

A boundary (discontinuity) separating air masses of different densities, one warmer and often higher in moisture content than the other.

Frontal fog

Fog formed when rain evaporates as it falls through a layer of cool air.

Frontal lifting

The lifting of air resulting when cool air acts as a barrier over which warmer, lighter air will rise.

Frost hazard

Weather conditions in which ice crystals form when the temperature falls to 0°C or below, killing flowers and produce. Also called a freeze hazard.

Fujita intensity scale (F-scale)

See Enhanced Fujita Scale.

General circulation models

Computer models that incorporate physics and chemistry, as well as human and biological interactions, to predict climate change.

Geosphere

The solid Earth, the largest of Earth's four major spheres.

Geostationary Operational Environmental Satellite (GOES)

A satellite that remains over a fixed point because its rate of travel corresponds to Earth's rate of rotation. Because the satellite must orbit at distances of about 35,000 kilometers, images from this type of satellite are not as detailed as those from polar satellites.

Geostrophic wind

A wind, usually above a height of 600 meters, that blows parallel to the isobars.

Glaze

See Freezing rain.

Global circulation

The general circulation of the atmosphere; the average flow of air over the entire globe.

Glory

A series of rings of colored light, most commonly appearing around the shadow of an airplane that is projected on clouds below.

Gradient wind

The curved airflow pattern around a pressure center resulting from a balance among pressure-gradient force, Coriolis force, and centrifugal force.

Graupel

"Soft hail" that forms as rime collects on snow crystals to produce irregular masses of "soft" ice.

Greenhouse effect

The transmission of shortwave solar radiation by the atmosphere coupled with the selective absorption of longer-wavelength terrestrial radiation, especially by water vapor and carbon dioxide, resulting in warming of the atmosphere.

Greenhouse gases

Gases in the atmosphere that absorb infrared (longwave) radiation emitted by Earth.

Growing degree-days

A practical application of temperature data for determining the approximate date when crops will be ready for harvest.

Gust front

The boundary separating the cold downdraft from a thunderstorm and the relatively warm, moist surface air. Lifting along this boundary may initiate the development of thunderstorms.

Gyre

Nearly circular ocean current.

Hadley cell

The thermally driven circulation system of equatorial and tropical latitudes consisting of two convection cells, one in each hemisphere. The existence of this circulation system was first proposed by George Hadley in 1735 to explain the trade winds.

Hail

Precipitation in the form of hard, round pellets or irregular lumps of ice that may have concentric shells formed by the successive freezing of layers of water.

Halo

A narrow whitish ring of large diameter centered around the Sun. The commonly observed *22° halo* subtends an angle of 22° from the observer.

Heat

The kinetic energy of random molecular motion.

Heat budget

The balance of incoming and outgoing radiation.

Heating degree-day

Each degree of temperature of the daily mean below 65°F is counted as one heating degree-day. The amount of heat required to maintain a certain temperature in a building is proportional to the heating degree-days total.

Heat stress index

The apparent temperature on a hot, humid day.

High cloud

A cloud that normally has its base above 6000 meters; the base may be lower in winter and at high-latitude locations.

Highland climate

Complex pattern of climate conditions associated with mountains. Highland climates are characterized by large differences that occur over short distances.

Horse latitudes

A belt of calms or light variable winds and subsiding air located near the center of the subtropical high.

Hot tower

Very intense thunderstorms seen by satellite in a hurricane before it intensifies.

Humid continental climate

A relatively severe climate characteristic of broad continents in the middle latitudes between approximately 40° and 50° north latitude. This climate is not found in the Southern Hemisphere, where the oceans dominate the middle latitudes.

Humidity

A general term referring to water vapor in the air.

Humid subtropical climate

A climate generally located on the eastern side of a continent and characterized by hot, sultry summers and cool winters.

Hurricane

A tropical cyclonic storm having minimum winds of 119 kilometers per hour; also known as *typhoon* (western Pacific) and *cyclone* (Indian Ocean).

Hurricane warning

A warning issued when sustained winds of 119 kilometers per hour or higher are expected within a specified coastal area in 24 hours or less.

Hurricane watch

An announcement aimed at specific coastal areas that a hurricane poses a possible threat, generally within 36 hours.

Hydrogen bonds

The attractive force that exists between hydrogen atoms in one water molecule and oxygen atoms in another water molecule.

Hydrologic cycle

The continuous movement of water from the oceans to the atmosphere (by evaporation), from the atmosphere to the land (by condensation and precipitation), and from the land back to the sea (via stream flow).

Hydrophobic nuclei

Particles that are not efficient condensation nuclei. Small droplets will form on them whenever the relative humidity reaches 100 percent.

Hydrosphere

The water portion of our planet; one of the traditional subdivisions of Earth's physical environment.

Hydrostatic balance

The balance maintained between the force of gravity and the vertical pressure gradient that does not allow air to escape to space.

Hygrometer

An instrument designed to measure relative humidity.

Hygroscopic nuclei

Condensation nuclei having a high affinity for water, such as salt particles.

Hypothesis

A tentative explanation that is tested to determine whether it is valid.

Ice cap climate

A climate that has no monthly means above freezing and supports no vegetative cover except in a few scattered high mountain areas. This climate, with its perpetual ice and snow, is confined largely to the ice sheets of Greenland and Antarctica.

Icelandic low

A large cell of low pressure centered over Iceland and southern Greenland in the North Atlantic during the winter.

Ideal gas law

The pressure exerted by a gas is proportional to its density and absolute temperature.

Inclination of the axis

The tilt of Earth's axis from the perpendicular to the plane of Earth's orbit (plane of the ecliptic). Currently, the inclination is about 23½° away from the perpendicular.

Inferior mirage

A mirage in which the image appears below the true location of the object.

Infrared radiation

Radiation with a wavelength from 0.7 to 200 micrometers.

Instrument shelter

A white box having louvered sides to permit the free movement of air through it while shielding the instruments from direct sunshine, heat from the ground, and precipitation.

Interface

A common boundary where different parts of a system interact.

Interference

A phenomenon that occurs when light rays of different frequencies (i.e., colors) meet. Such interference results in the cancellation or subtraction of some frequencies, which is responsible for the colors associated with coronas.

Internal reflection

A reflection that occurs when light traveling through a transparent material, such as water, reaches the opposite surface and is reflected back into the material. This is an important factor in the formation of optical phenomena such as rainbows.

Intertropical convergence zone (ITCZ)

The zone of general convergence between the Northern and Southern Hemisphere trade winds.

Ionosphere

A complex atmospheric zone of ionized gases extending between 80 and 400 kilometers, thus coinciding with the lower thermosphere and heterosphere.

Iridescent cloud

Brightly colored areas near the edge of a cloud caused by diffraction.

Isobar

A line drawn on a map connecting points of equal barometric pressure, usually corrected to sea level.

Isohyet

A line connecting places having equal rainfall.

Isotach

A line connecting places having equal wind speed.

Isotherm

A line connecting points of equal air temperature.

ITCZ

See Intertropical convergence zone.

Jet streak

Areas of higher-velocity winds found within the jet stream.

Jet stream

Swift geostrophic airstreams in the upper troposphere that meander in relatively narrow belts.

Katabatic wind

The flow of cold, dense air downslope under the influence of gravity; the direction of flow is controlled largely by topography. Also called *fall wind*.

Kelvin scale

A temperature scale (also called the *absolute scale*) used primarily for scientific purposes and having intervals equivalent to those on the Celsius scale but beginning at absolute zero.

Kinetic energy

Energy associated with an object in motion.

Köppen classification system

Devised by Wladimir Köppen, a system for classifying climates that is based on mean monthly and annual values of temperature and precipitation.

Lake-effect snow

Snow showers associated with a cP air mass to which moisture and heat are added from below as it traverses a large and relatively warm lake (such as one of the Great Lakes), rendering the air mass humid and unstable.

Land breeze

A local wind blowing from the land toward the sea during the night in coastal areas.

La Niña

An episode of strong trade winds and unusually low sea-surface temperatures in the central and eastern Pacific. The opposite of *El Niño*.

Lapse rate

See Environmental lapse rate; Normal lapse rate.

Latent heat

The energy absorbed or released during a change of state.

Latent heat of condensation

The energy released when water vapor changes to the liquid state. The amount of energy released is equivalent to the amount absorbed during evaporation.

Latent heat of vaporization

The energy absorbed by water molecules during evaporation. It varies from about 600 calories per gram for water at 0°C to 540 calories per gram at 100°C.

Law of reflection

See Reflection, law of.

Leader

The conductive path of ionized air that forms near a cloud base prior to a lightning stroke. The initial conductive path is referred to as a *step leader* because it extends itself earthward in short, nearly invisible bursts. A *dart leader*, which is continuous and less branched than a step leader, precedes each subsequent stroke along the same path.

Lenticular clouds

A lens-shaped cloud that forms at the crest of air oscillations downstream of a mountain.

Level of free convection

The height of a rising air parcel when it first becomes warmer than the surrounding environment.

Lifting condensation level

The height at which rising air that is cooling at the dry adiabatic rate becomes saturated and condensation begins.

Lightning

A sudden flash of light generated by the flow of electrons between oppositely charged parts of a cumulonimbus cloud or between the cloud and the ground.

Liquid-in-glass thermometer

A device for measuring temperature that consists of a tube with a liquid-filled bulb at one end. The expansion or contraction of the fluid indicates temperature.

Lithosphere

The rocky outer layer of Earth that lies beneath the atmosphere and ocean.

Localized convective lifting

The process in which a parcel of air warmed at the surface becomes buoyant and rises above the lifting condensation level to form clouds.

Long-range forecast

An estimate of precipitation and temperatures for a period beyond 3 to 5 days, usually for 30-day periods. Such forecasts are not as detailed or reliable as those for shorter periods.

Longwave radiation

A reference to radiation emitted by Earth. Wavelengths are roughly 20 times longer than those emitted by the Sun.

Looming

A mirage that allows objects that are below the horizon to be seen.

Low cloud

A cloud that forms below a height of about 2000 meters.

Macroscale winds

Phenomena such as cyclones and anticyclones that persist for days or weeks and have a horizontal dimension of hundreds to several thousands of kilometers; also, features of the atmospheric circulation that persist for weeks or months and have horizontal dimensions of up to 10,000 kilometers.

Mammatus cloud

Cloud pockets hanging downward from the underside of the cloud's anvil or its base.

Marine climate

A climate dominated by the ocean; because of the moderating effect of water, sites having this climate are considered relatively mild.

Marine west coast climate

A climate found on windward coasts from latitudes 40° to 65° and dominated by maritime air masses. In this climate, winters are mild and summers are cool.

Maritime (m) air mass

An air mass that originates over the ocean. These air masses are relatively humid.

Mature stage

The second of the three stages of a thunderstorm. This stage is characterized by violent weather as downdrafts exist side-by-side with updrafts.

Maximum thermometer

A thermometer that measures the maximum temperature for a given period in time, usually 24 hours. A constriction in the base of the glass tube allows mercury to rise but prevents it from returning to the bulb until the thermometer is shaken or whirled.

Mediterranean climate

A climate located on the west sides of continents between latitudes 30° and 45°. It is the only humid climate with a strong winter precipitation maximum.

Melting

The change of state from solid to liquid.

Mercury barometer

A mercury-filled glass tube in which the height of the column of mercury is a measure of air pressure.

Meridional flow

A flow pattern that is predominately north–south.

Mesocyclone

A vertical cylinder of cyclonically rotating air (3 to 10 kilometers in diameter) that develops in the updraft of a severe thunderstorm and that often precedes the development of damaging hail or tornadoes.

Mesopause

The boundary between the mesosphere and the thermosphere.

Mesoscale convective complex (MCC)

A slow-moving roughly circular cluster of interacting thunderstorm cells covering an area of thousands of square kilometers that may persist for 12 hours or more.

Mesoscale winds

Small convective cells that exist for minutes or hours, such as thunderstorms, tornadoes, and land and sea breezes. Typical horizontal dimensions range from 1 to 100 kilometers.

Mesosphere

The zone in the atmosphere above the stratosphere that is characterized by temperatures decreasing with height.

Meteogram

Graphical representation of a time series of weather data, such as temperature or pressure.

Meteorologist

See Meteorology.

Meteorology

The scientific study of the atmosphere and atmospheric phenomena; the study of weather and climate.

Microburst

A sudden, powerful downward burst of air from a thunderstorm.

Micrometer

A unit of length equal to one millionth of a meter.

Microscale winds

Phenomena such as turbulence, with life spans of less than a few minutes that affect small areas and are strongly influenced by local conditions of temperature and terrain.

Middle cloud

A cloud occupying the height range from 2000 to 6000 meters.

Midlatitude cyclone

A large low-pressure center with diameter often exceeding 1000 kilometers that moves from west to east and may last from a few days to more than a week and usually has a cold front and a warm front extending from the central area of low pressure.

Midlatitude desert

A climate region in the interior of large midlatitude land masses where evaporation exceeds precipitation and vegetation is sparse.

Midlatitude jet stream

A jet stream that migrates between latitudes 30° and 70°.

Midlatitude steppe

A climate region in the interior of large midlatitude land masses characterized by meager and unreliable precipitation and unforested grassland.

Millibar

The standard unit of pressure measurement used by the National Weather Service. One millibar (mb) equals 100 newtons per square meter.

Minimum thermometer

A thermometer that measures the minimum temperature for a given period of time, usually 24 hours. By checking the small dumbbell-shaped index, the observer can read the minimum temperature.

Mirage

An optical effect of the atmosphere caused by refraction, in which the image of an object appears displaced from its true position.

Mist

Droplets small enough that they are barely felt, typically associated with stratus clouds.

Mistral

A cold northwest wind that blows into the western Mediterranean basin from higher elevations to the north.

Mixing depth

The height to which convectional movements extend above Earth's surface. The greater the mixing depths, the better the air quality.

Mixing ratio

The mass of water vapor in a unit mass of dry air; commonly expressed as grams of water vapor per kilogram of dry air.

Model Output Statistics (MOS)

Statistical methods used to modify machine-generated numerical forecasts by making comparisons of the accuracy of previous forecasts, to correct for errors the model tends to make consistently.

Monsoon

The seasonal reversal of wind direction associated with large continents, especially Asia. In winter, the wind blows from land to sea; in summer, it blows from sea to land.

Monthly mean temperature
The mean temperature for a month that is calculated by averaging the daily means.

Mountain breeze
The nightly downslope winds commonly encountered in mountain valleys.

Multicell thunderstorm
Numerous thunderstorm cells in various stages of development clustered together.

Multiple-vortex tornado
A tornado that contains several smaller intense whirls called suction vortices that orbit the center of the larger tornado circulation.

National Centers for Environmental Protection (NCEP)
The office responsible for making predictions about the future state of the atmosphere.

National Hurricane Center (NHC)
The office responsible for forecasting and monitoring tropical weather systems.

National Weather Service (NWS)
The federal agency responsible for gathering and disseminating weather-related information.

Negative-feedback mechanism

As used in climatic change, any effect that is opposite of the initial change and tends to offset it.

Newton

A unit of force used in physics. One newton is the force necessary to accelerate 1 kilogram of mass 1 meter per second squared.

Nimbostratus

A low layer of dark gray clouds that is a primary precipitation producer.

Nimbus

A term used in the name of cloud types that are major precipitation producers, such as nimbostratus and cumulonimbus.

Nor'easter

The term used to describe the weather associated with an incursion of mP air into the Northeast from the North Atlantic; strong northeast winds, freezing or near-freezing temperatures, and the possibility of precipitation make this an unwelcome weather event.

Normal lapse rate

The average drop in temperature with increasing height in the troposphere; about 6.5°C per kilometer.

Nowcasting

Short-term weather forecasting techniques that are generally applied to predicting severe weather.

Numerical weather prediction (NWP)

Forecasting the behavior of atmospheric disturbances based upon the solution of the governing fundamental equations of hydrodynamics, subject to the observed initial conditions. Because of the vast number of calculations involved, high-speed computers are always used for NWP.

Obliquity

The angle between the planes of Earth's equator and orbit.

Occluded front

A front formed when a cold front overtakes a warm front.

Occlusion

The overtaking of one front by another.

Ocean current

The mass movement of ocean water that is either wind driven or initiated by temperature and salinity conditions that alter the density of seawater.

Orbit

The elliptical path that Earth travels around the sun once each year.

Ordinary cell thunderstorm.

A localized thunderstorm that forms in a warm, moist, unstable air mass. This type of storm occurs most frequently in the afternoon in spring and summer.

Orographic lifting

The process in which mountains or highlands act as barriers to the flow of air and force the air to ascend. The air cools adiabatically, and clouds and precipitation may result.

Outgassing

The release of gases dissolved in molten rock.

Overrunning

Warm air gliding up a retreating cold air mass.

Overshooting top

The bulge at the top of strong thunderstorms that represents the top of the updraft.

Oxygen-isotope analysis

A method of deciphering past temperatures based on the precise measurement of the ratio between two isotopes of oxygen, 16O and 18O. Analysis is commonly made of seafloor sediments and cores from ice sheets.

Ozone

A molecule of oxygen containing three oxygen atoms.

Paleoclimatology

The study of ancient climates; the study of climate and climate change prior to the period of instrumental records using proxy data.

Parcel

An imaginary volume of air enclosed in a thin elastic cover. Typically a parcel is considered to be a few hundred cubic meters in volume and is assumed to act independently of the surrounding air.

Particulate matter

A general term used for a mixture of tiny solid particles and liquid drops suspended in air.

Perihelion

The point in the orbit of a planet closest to the Sun.

Permafrost

The permanent freezing of the subsoil in tundra regions.

Persistence forecast

A forecast that assumes that the weather occurring upstream will persist and move on and will affect the areas in its path in much the same way. Persistence forecasts do not account for changes that might occur in the weather system.

pH scale

A 0-to-14 scale that is used for expressing the exact degree of acidity or alkalinity of a solution. A pH of 7 signifies a neutral solution. Values below 7 signify an acid solution, and values above 7 signify an alkaline solution.

Photochemical reaction

A chemical reaction in the atmosphere triggered by sunlight, often yielding a secondary pollutant.

Photochemical smog

Air pollution that consists of a noxious mixture of secondary pollutants, mainly gases and particles of nitrogen-based compounds and ozone, that produces a yellowish haze over cities.

Plane of the ecliptic

The plane of Earth's orbit around the Sun.

Planetary-scale wind

Large-scale flow pattern that extends around a significant portion of Earth and can remain for weeks at a time.

Plate tectonics theory

A theory which states that the outer portion of Earth is made up of several individual pieces, called *plates*, which move in relation to one another upon a partially molten zone below. As plates move, so do continents, which explains some climatic changes in the geologic past.

Polar (P) air mass

A cold air mass that forms in a high-latitude source region.

Polar cell

Atmospheric circulation driven by subsidence near the poles that produces a surface flow that moves equatorward.

Polar climate

A climate in which the mean temperature of the warmest month is below 10°C; a climate that is too cold to support the growth of trees.

Polar easterlies

In the global pattern of prevailing winds, winds that blow from the polar high toward the subpolar low. These winds, however, should not be thought of as persistent winds, such as the trade winds.

Polar front

The stormy frontal zone separating air masses of polar origin from air masses of tropical origin.

Polar front theory

A theory developed by J. Bjerknes and other Scandinavian meteorologists in which the polar front, separating polar and tropical air masses, gives rise to cyclonic disturbances that intensify and move along the front and pass through a succession of stages.

Polar high

Anticyclones that are assumed to occupy the inner polar regions and are believed to be thermally induced, at least in part.

Polar jet stream

A swift airstream in the upper troposphere that meanders in a relatively narrow belt between the polar cell and the Ferrel cell. This is also called the polar jet.

Polar-orbiting Operational Environmental Satellite (POES)

Satellite that orbits the poles at rather low altitudes of a few hundred kilometers and requires only 100 minutes per orbit.

Positive-feedback mechanism

As used in climatic change, any effect that acts to reinforce an initial change.

Potential energy

Energy that exists by virtue of a body's position with respect to gravity.

Precession

The slow migration of Earth's axis that traces a cone over a period of 26,000 years.

Precipitation fog

See Frontal fog.

Pressure gradient

The amount of pressure change occurring over a given distance.

Pressure gradient force

A force acting on air from higher to lower pressure. This force starts air moving to produce wind.

Prevailing westerlies

The dominant west-to-east motion of the atmosphere that characterizes the regions on the poleward side of the subtropical highs.

Prevailing wind

A wind that consistently blows from one direction more than from any other.

Primary pollutant

A pollutant emitted directly from an identifiable source.

Probability of Precipitation (PoP)

A forecast given as a percentage probability for precipitation.

Prognostic chart

A computer-generated forecast showing the expected pressure pattern at a specified future time. Anticipated positions of fronts are also included. They usually represent the graphical output associated with a numerical weather prediction model.

Proxy data

Data gathered from natural recorders of climate variability, such as tree rings, ice cores, and ocean-floor sediments.

Psychrometer

A device consisting of two thermometers (wet bulb and dry bulb) that is rapidly whirled and, with the use of tables, yields the relative humidity and dew point.

Qualitative forecast

A forecast which describes an aspect of weather that can be observed but not easily measured.

Quantitative forecast

A forecast which describes an aspect of weather than can be easily measured.

Quantitative Precipitation Forecast (QPF)

A forecast that depicts the amount of precipitation (in inches) expected to fall over an area within a specified period of time.

Quaternary Ice Age

The last major period of glaciation, occurring about 18,000 years ago.

Radar scatterometer

A satellite-based instrument that determines wind speed using ocean waves.

Radiation

The wavelike energy emitted by any substance that possesses heat. This energy travels through space at 300,000 kilometers per second (the speed of light).

Radiation fog

Fog resulting from radiation cooling of the ground and adjacent air; primarily a nighttime and early morning phenomenon.

Radiosonde

A lightweight package of weather instruments fitted with a radio transmitter and carried aloft by a balloon.

Rain

Liquid drops falling from nimbostratus or cumulonimbus clouds.

Rain band

Intense thunderstorms that surround the eye wall in concentric bands.

Rainbow
A luminous arc formed by the refraction and reflection of light in drops of water.

Rain shadow desert
A dry area on the lee side of a mountain range.

Rawinsonde
A radiosonde that is tracked by radio-location devices in order to obtain data on upper-air winds.

Reflection
The process where light bounces back from an object at the same angle and intensity at which it was received.

Reflection, law of
A law that states that the angle of incidence (incoming ray) is equal to the angle of reflection (outgoing ray).

Refraction
The bending of light as it passes obliquely from one transparent medium to another.

Relative humidity
The ratio of the air's water-vapor content to its water-vapor capacity.

Return stroke
The electric discharge resulting from the downward (earthward) movement of electrons from successively higher levels along the conductive path of lightning.

Revolution

The motion of one body about another, as Earth about the Sun.

Ridge

An elongate region of high atmospheric pressure.

Rime

A delicate accumulation of ice crystals formed when supercooled fog or cloud droplets freeze on contact with objects.

Roll cloud

A cloud formation that looks like a rope along the leading edge of a thunderstorm.

Rossby waves

Upper-air waves in the middle and upper troposphere of the middle latitudes with wavelengths of from 4000 to 6000 kilometers; named for C. G. Rossby, the meteorologist who developed the equations for parameters governing the waves.

Rotation

The spinning of a body, such as Earth, about its axis.

Saffir–Simpson scale

A scale, from 1 to 5, used to rank the relative intensities of hurricanes.

Santa Ana

The local name given a foehn wind in southern California.

Saturation

The maximum possible quantity of water vapor that the air can hold at any given temperature and pressure.

Saturation vapor pressure

The vapor pressure, at a given temperature, wherein the water vapor is in equilibrium with a surface of pure water or ice.

Savanna

A tropical grassland, usually with scattered trees and shrubs.

Scattering

The process in which light bounces off of an object in many directions.

Sea breeze

A local wind that blows from the sea toward the land during the afternoon in coastal areas.

Sea-level pressure

Pressure that has been converted to the pressure at sea level so that altitude effects can be removed.

Secondary pollutant

A pollutant that is produced in the atmosphere by chemical reactions occurring among primary pollutants.

Semiarid

See Steppe.

Sensible heat

The heat we can feel and measure with a thermometer.

Severe thunderstorm

A thunderstorm that produces frequent lightning, locally damaging wind, or hail that is 2 centimeters or more in diameter. In the middle latitudes, most thunderstorms form along or ahead of cold fronts.

Sheet lightning

A type of lightning that produces a bright, but diffused illumination in parts of the cloud.

Shelf cloud

A low, wedge-shaped cloud formation along the leading edge of a thunderstorm.

Shortwave radiation

Radiation emitted by the Sun.

Siberian high

The high-pressure center that forms over the Asian interior in January and produces the dry winter monsoon for much of the continent.

Skew-T/Log P diagram (Skew-T)

The most commonly used type of thermodynamic diagram.

Skill

See Forecast skill.

Sleet

Frozen or semifrozen rain formed when raindrops pass through a subfreezing layer of air.

Smog

A word currently used as a synonym for general air pollution. It was originally created by combining the words “smoke” and “fog.”

Snow

Precipitation in the form of white or translucent ice crystals, chiefly in complex branched hexagonal form and often clustered into snowflakes.

Snow pillow

An instrument consisting of a panel on the ground that measures the weight of snow that collects on it.

Solstice

The point in time when the vertical rays of the Sun are striking either the Tropic of Cancer (summer solstice in the Northern Hemisphere) or the Tropic of Capricorn (winter solstice in the Northern Hemisphere). Solstice represents the longest or shortest day (length of daylight) of the year.

Sounding

See Atmospheric sounding.

Source region

The area where an air mass acquires its characteristic properties of temperature and moisture.

Southern oscillation

The seesaw pattern of atmospheric pressure change that occurs between the eastern and western Pacific. The interaction of this effect and that of El Niño can cause extreme weather events in many parts of the world.

Specific heat

The amount of heat needed to raise 1 gram of a substance 1°C at sea-level atmospheric pressure.

Specific humidity

The mass of water vapor per unit mass of air, including the water vapor (usually expressed as grams of water vapor per kilogram of air).

Squall line

Any nonfrontal line or narrow band of active thunderstorms.

Stable air

Air that resists vertical displacement. If it is lifted, adiabatic cooling will cause its temperature to be lower than the surrounding environment; if it is allowed, it will sink to its original position.

Standard rain gauge

A gauge that has a diameter of about 20 centimeters and funnels rain into a cylinder that magnifies precipitation amounts by a factor of 10, allowing for accurate measurement of small amounts.

Station pressure

The actual pressure measured at a weather station before it is converted to sea-level pressure.

Stationary front

A situation in which the surface position of a front does not move; the flow on either side of such a boundary is nearly parallel to the position of the front.

Statistical methods (forecasting)

See Model Output Statistics.

Steam fog

Fog that has the appearance of steam and that is produced by evaporation from a warm water surface into the cool air above.

Steppe

One of the two types of dry climate; a marginal and more humid variant of the desert that separates it from bordering humid climates. Steppe also refers to the short-grass vegetation associated with this semiarid climate.

Stepped leader

See Leader.

Storm Prediction Center (SPC)

The office responsible for forecasting severe weather.

Storm surge

The abnormal rise of the sea along a shore as a result of strong winds.

Straight-line winds

Winds behind the gust front of a thunderstorm that flow in a straight line, rather than rotating like a tornado.

Stratocumulus

Low-level soft, gray clouds in globular patches or rolls.

Stratopause

The boundary between the stratosphere and the mesosphere.

Stratosphere

The zone of the atmosphere above the troposphere characterized at first by isothermal conditions and then a gradual temperature increase. Earth's ozone is concentrated here.

Stratus

One of three basic cloud forms; also the name of a type of low cloud. Stratus clouds are sheets or layers that cover much or all of the sky.

Stroke

One of the individual components that make up a flash of lightning. There are usually three to four strokes per flash, roughly 50 milliseconds apart.

Subarctic climate

A climate found north of the humid continental climate and south of the polar climate that is characterized by bitterly cold winters and short cool summers. Places within this climatic realm experience the highest annual temperature ranges on Earth.

Sublimation

The process whereby a solid changes directly to a gas, without going through the liquid state.

Subpolar low

Low pressure located at about the latitudes of the Arctic and Antarctic Circles. In the Northern Hemisphere, the low takes the form of individual oceanic cells; in the Southern Hemisphere, there is a deep and continuous trough of low pressure.

Subsidence

An extensive sinking motion of air, most frequently occurring in anticyclones. The subsiding air is warmed by compression and becomes more stable.

Subsidence inversion

A temperature inversion caused by sinking air, generally associated with a high pressure system.

Subtropical desert

A climate region associated with the subtropical high where evaporation exceeds precipitation and little to no vegetation grows.

Subtropical jet stream

A swift airstream in the upper troposphere that meanders in a relatively narrow belt in the winter hemisphere between the *Hadley Cell* and the

Ferrel Cell.

Subtropical high

Several semipermanent anticyclonic centers characterized by subsidence and divergence located roughly between latitudes 25° and 35°.

Subtropical steppe

A climate region associated with the margins of the subtropical high, characterized by meager and unreliable precipitation and unforested grassland.

Summer solstice

See Solstice.

Sun dogs

Two bright spots of light, sometimes called "mock suns," that sit at a distance of 22° on either side of the Sun.

Sun pillar

Shafts of light caused by reflection from ice crystals that extend upward or, less commonly, downward from the Sun when the Sun is near the horizon.

Sunspot

A dark area on the Sun associated with powerful magnetic storms that extend from the Sun's surface deep into the interior.

Supercell

A type of thunderstorm that consists of a single, persistent, and very powerful cell (updraft and downdraft) and that often produces severe weather, including hail and tornadoes.

Supercooled water

Water droplets that remain in the liquid state at temperatures well below 0°C.

Superior mirage

A mirage in which the image appears above the true position of the object.

Surface weather analysis

Surface weather maps that organize a vast array of weather data so users can discern large-scale weather patterns.

Sustained winds

Wind speeds determined by averaging observed wind values over a 1-minute time period.

Synoptic-scale wind

The macroscale circulation that is weather-map scale.

System

A collection of numerous interacting parts, or subsystems, that form a complex whole. The hydrologic cycle is one example.

Taiga

The northern coniferous forest; also a name applied to the subarctic climate.

Teleconnection

The link between the weather occurring in widely separated regions of the globe.

Temperature

A measure of the degree of hotness or coldness of a substance.

Temperature controls

Factors that cause variations in temperature from place to place, such as latitude and altitude.

Temperature gradient

The amount of temperature change per unit of distance.

Temperature inversion

A layer in the atmosphere of limited depth where the temperature increases rather than decreases with height.

Theory

A well-tested and widely accepted view that explains certain observable facts.

Thermal

An example of convection that involves the upward movements of warm, less dense air. In this manner, heat is transported to greater heights.

Thermal low

An area of low atmospheric pressure created by abnormal surface heating.

Thermistor

An electric thermometer consisting of a conductor whose resistance to the flow of current is temperature dependent; commonly used in radiosondes.

Thermodynamic diagram

A graph that displays temperature, dew-point temperature, and wind that is collected by a radiosonde.

Thermometer

An instrument for measuring temperature; in meteorology, a thermometer is generally used to measure the temperature of the air.

Thermosphere

The zone of the atmosphere beyond the mesosphere in which there is a rapid rise in temperature with height.

Thunder

The sound emitted by rapidly expanding gases along the channel of a lightning discharge.

Thunderstorm

A storm produced by a cumulonimbus cloud and always accompanied by lightning and thunder. It is of relatively short duration and usually accompanied by strong wind gusts, heavy rain, and sometimes hail.

Tipping-bucket gauge

A recording rain gauge consisting of two compartments ("buckets"), each capable of holding 0.025 centimeter of water. When one compartment fills, it tips, and the other compartment takes its place.

Tornado

A violently rotating column of air attended by a funnel-shaped or tubular cloud extending downward from a cumulonimbus cloud.

Tornado warning

A warning issued when a tornado has actually been sighted in an area or is indicated by radar.

Tornado watch

A forecast issued for areas of about 65,000 square kilometers, indicating that conditions are such that tornadoes may develop; a tornado watch is intended to alert people to the possibility of tornadoes.

Towering

A mirage in which the size of an object is magnified.

Trace gases

Gases in the atmosphere that are important despite their small concentration.

Trace of precipitation

An amount of precipitation less than 0.025 centimeter.

Track forecast cone

A forecasting product that shows the current location of a hurricane and its predicted track using a cone that widens to indicate uncertainty at later time periods.

Trade winds

Two belts of winds that blow almost constantly from easterly directions and are located on the equatorward sides of the subtropical highs.

Transmission

Passage of light through a substance without being absorbed or scattered.

Transpiration

The release of water vapor to the atmosphere by plants.

Trend forecast

A short-range forecasting technique which assumes that the weather occurring upstream will persist and move on to affect the area in its path.

Tropic of Cancer

The parallel of latitude, 23½° north latitude, marking the northern limit of the Sun′s vertical rays.

Tropic of Capricorn

The parallel of latitude, 23½° south latitude, marking the southern limit of the Sun′s vertical rays.

Tropical (T) air mass

A warm-to-hot air mass that forms in the subtropics.

Tropical depression

By international agreement, a tropical cyclone with maximum winds that do not exceed 61 kilometers per hour.

Tropical disturbance

A term used by the National Weather Service for a cyclonic wind system in the tropics that is in its formative stages.

Tropical monsoon climate

A climate region in tropical areas that experience a pronounced seasonal shift in wind pattern.

Tropical rain forest

A luxuriant broadleaf evergreen forest; also the name given the climate associated with this vegetation.

Tropical storm

By international agreement, a tropical cyclone with maximum winds between 61 and 115 kilometers per hour.

Tropical wave

See Easterly wave.

Tropical wet climate

A climate region noted for its high temperatures and abundant rainfall year round.

Tropical wet and dry climate

A climate that is transitional between the wet tropics and the subtropical steppes.

Tropopause

The boundary between the troposphere and the stratosphere.

Troposphere

The lowermost layer of the atmosphere, marked by considerable turbulence and, in general, a decrease in temperature with increasing height.

Trough

An elongate region of low atmospheric pressure.

Tundra

A treeless region of grasses, sedges, mosses, and lichens.

Tundra climate

A treeless climate found almost exclusively in the Northern Hemisphere and at high altitudes in many mountainous regions dominated by a long, bitterly cold winter.

Ultraviolet radiation

Radiation with a wavelength from 0.2 to 0.4 micrometer.

Unstable air

Air that does not resist vertical displacement. If it is lifted, its temperature will not cool as rapidly as the surrounding environment, and so it will continue to rise on its own.

Upslope fog

Fog created when air moves up a slope and cools adiabatically.

Upwelling

The process by which deep, cold, nutrient-rich water is brought to the surface, usually by coastal currents that move water away from the coast.

Urban heat island

A city area where temperatures are generally higher than in surrounding rural areas.

U.S. standard atmosphere

The idealized vertical distribution of atmospheric pressure, temperature, and density that represents average conditions in the atmosphere.

Valley breeze

The daily upslope winds commonly encountered in a mountain valley.

Vapor pressure

The part of the total atmospheric pressure attributable to its water-vapor content.

Vernal equinox

See Equinox.

Vertical directional shear

A change in wind direction with height.

Vertical speed shear

A change in wind speed with height.

Virga

Wisps or streaks of water or ice particles that fall out of a cloud and evaporate before reaching Earth′s surface.

Visibility

The greatest distance at which prominent objects can be seen and identified by unaided, normal eyes.

Visible light

Radiation with a wavelength from 0.4 to 0.7 micrometer.

Vog

Air pollution that is a combination of volcanic emissions and fog.

Wall cloud

A dark, low-hanging cloud below the base of a supercell thunderstorm caused by the rotating mesocyclone.

Warm conveyor belt

Airflow within a midlatitude cyclone that moves northward near the surface ahead of the cold front, then rises along the warm front boundary.

Warm front

The discontinuity at the forward edge of an advancing warm air mass that displaces cooler air in its path.

Warm-type occluded front

A front that forms when the air behind the cold front is warmer than the air underlying the warm front it is overtaking.

Wavelength

The horizontal distance separating successive crests or troughs.

Weather

The state of the atmosphere at any given time.

Weather analysis

The stage prior to developing a weather forecast. This stage involves collecting, compiling, and transmitting observational data.

Weather forecast

A prediction of the future state of the atmosphere.

Weather Forecast Office (WFO)

The office where weather forecasters create local and regional forecasts that are shared with the public.

Weather radar

An instrument run by the National Weather Service that is used to create maps showing the location and movement of precipitation.

Weighing gauge

A recording precipitation gauge consisting of a cylinder that rests on a spring balance.

Westerlies

See Prevailing westerlies.

Wet adiabatic rate

The rate of adiabatic temperature change in saturated air. The rate of temperature change is variable, but it is always less than the dry adiabatic rate.

Wind

Air flowing horizontally with respect to Earth's surface.

Windchill temperature index

A measure of apparent temperature that uses the effects of wind and temperature on the cooling rate of the human body. The windchill index translates the cooling power of the atmosphere with the wind to a temperature under nearly calm conditions.

Wind shear

A change in wind speed or direction with height.

Wind vane

An instrument used to determine wind direction.

Winter solstice

See Solstice.

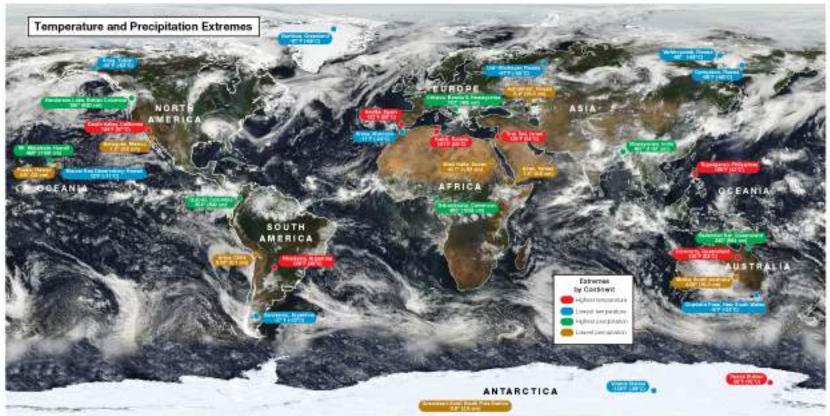
World Meteorological Organization (WMO)

Established by the United Nations, an organization that consists of more than 130 nations and is responsible for gathering needed observational data and compiling some general prognostic charts.

Zonal flow

A wind flow pattern that is predominately east–west.

Temperature and Precipitation Extremes



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Cloud Guide

High Clouds: Cloud Bases Above 6 km (20,000 ft)

Cirrus These clouds are made exclusively of ice crystals. They are not as horizontally extensive as cirrostratus clouds.

Cirrocumulus These high clouds can produce striking skies. Composed of ice crystals, they often contain linear bands, numerous patches of greater vertical development, or both.

Cirrostratus These are thin layered clouds composed of ice crystals. They are relatively indistinct and give the sky a whitish appearance.

Contrails A contrail is a long, narrow cloud that is formed as exhaust from a jet aircraft condenses in cold air at high altitude. Upper level winds may gradually cause contrails to spread out.

Middle Clouds: Cloud Bases 2–6 km (6,500–20,000 ft)

Altocumulus These midlevel clouds are horizontally layered but exhibit varying thicknesses across their bases. Thicker areas can be arranged as parallel linear bands or as a series of individual puffs.

Altocumulus (Lenticular) These clouds are marked by their lens-shaped appearance. They usually form downwind of mountain barriers as horizontal airflow is disrupted into a sequence of waves.

Altostratus These are midlevel, layered clouds that produce gray skies and obscure the Sun or Moon enough to make them appear as poorly defined bright spots. In this example, the setting sun brightens the clouds near the horizon but the gray appearance remains elsewhere.

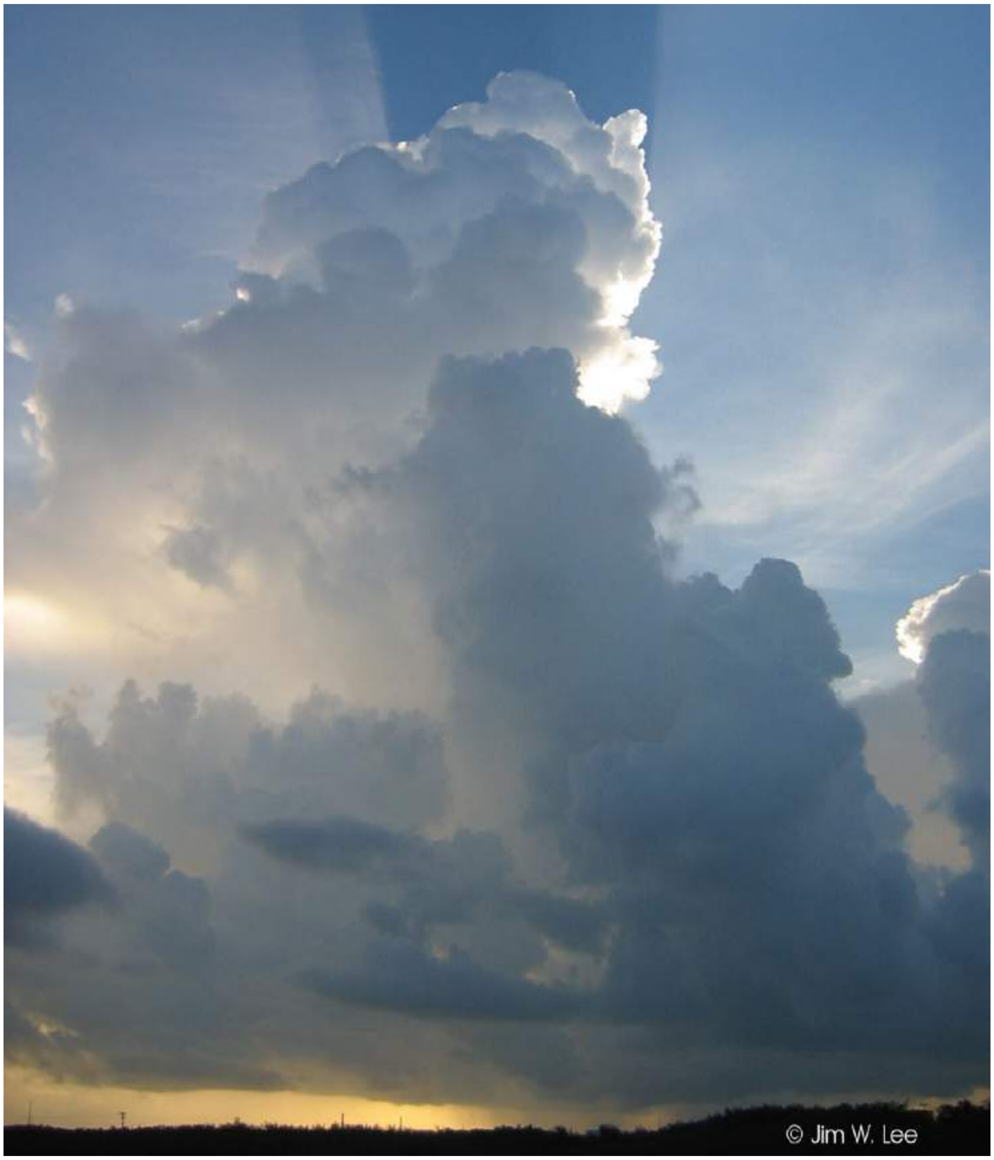
Altostratus (Multilayer) These are midlevel layered clouds that are dense enough to completely hide the Sun or Moon.

Low Clouds and Clouds of Vertical Development: Cloud Bases 0–2 km (0–6,500 ft)

Cumulus These clouds often have flat bottoms, rounded tops, and a "cellular" structure made up of individual clouds. (The word "cumulus" comes from the Latin word for "heap.") Cumulus clouds tend to grow vertically.

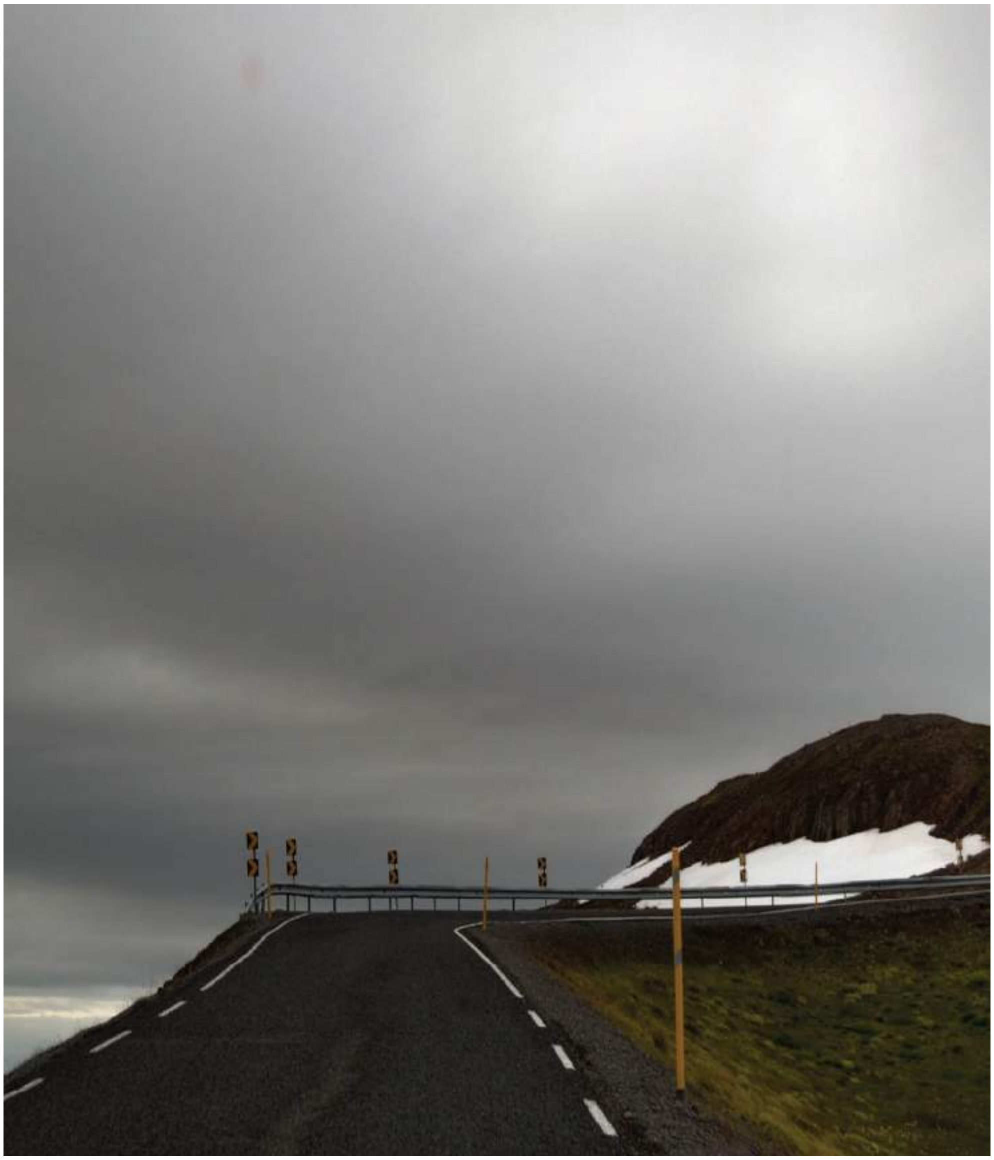
Cumulus Humilis Often called fair-weather cumulus, these small white individual masses lack conspicuous vertical development and rarely produce precipitation.

Cumulus Congestus These clouds have considerably more vertical development than cumulus humilis. They may produce heavy precipitation, but not the severe weather associated with some cumulonimbus clouds.



Stratocumulus These are low, layered clouds that have regions of some vertical development. Differences in thickness create varying degrees of darkness when seen from below.

Nimbostratus These low clouds are thick gray layers that contain sufficient water to yield light-to-moderate precipi-tation.



Cumulonimbus These clouds result from very strong updrafts that may push the cloud tops up to several kilometers into the stratosphere. Their character-istic feature is the anvil, a zone of ice crystals extending outward from the main portion of the cloud.

Cumulonimbus with Mammatus These are dramatic features asso-ciated with some cumulonimbus, resulting from strong downdrafts and turbulence along the bases or margins of the clouds.

Cumulonimbus with Wall Cloud A feature associated with some cumulonimbus clouds. When wall clouds are present, heavy rain, hail, and sometimes tornadoes can be expected.

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