The role of ice stream dynamics in deglaciation: Supplementary material

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1 The importance of resolving ice streams

We demonstrate above that the acceleration of ice streams strongly contributes to rapid deglaciation. Geomorphological observations (Margold et al., 2015) indicate that many paleo-ice streams were narrower than 50 km and more similar to those currently found in the Siple Coast region of the West Antarctic Ice Sheet. However, model studies of paleo ice sheets often involve long integrations of 10^4 to 10^5 years and consequently tend to use coarse horizontal resolution of 30-100 km. Thus, they may not be able to fully resolve many of the ice streams known to contribute to paleo ice sheet flow. Furthermore, most paleoclimate studies use shallow ice models which may be ill-posed with respect to consistent simulation of ice streams (Hindmarsh, 2011) and are only capable of resolving topographically constrained ice streams (e.g., Stokes and Tarasov, 2010; Ganopolski and Calov, 2011; Abe-Ouchi et al., 2013). Simulating ice streams which arise due to weak frictional resistance at the bed and low driving stress requires the inclusion of lateral viscous stresses (Hindmarsh, 2009), which have only recently been incorporated in paleo ice sheet models (Golledge et al., 2012; Pollard et al., 2012). We now demonstrate explicitly the importance of fine horizontal model resolution for resolving ice streams and simulating the full ice sheet volume decrease associated with rapid deglaciation.

In order to be able to run many simulations at a variety of grid spacings, we change the model configuration for the simulations in this section to have a coastline closer to the domain center and fewer ice streams at steady-state. The resulting ice sheets rest on a bed with half the terrestrial diameter of idealized simulation in this study ($L = 500$ km) and have 28 ice streams of 40 km width, accounting for approximately the same proportion of the ice sheet margin (25%) at steady-state. As in other simulations, the ice sheet grows, and we apply a change in forcing at 40 kyr. We repeat this simulation for a variety of different horizontal grid resolutions, from 50 km, down to 3 km. Figure S1 shows the response in simulated ice volume, surface mass balance and calving discharge for different horizontal resolutions. Ice volume loss during deglaciation is small or absent entirely in the coarse resolution model simulations (solid magenta and red lines in Figure S1a). At horizontal resolutions coarser than 20 km, the strips of weak till that are specified in the bed configuration are either a single grid point wide (red) or missed entirely by the grid (magenta). An ice sheet simulated using a coarse grid and with poorly-resolved ice streams is thicker both in the interior and near the margins

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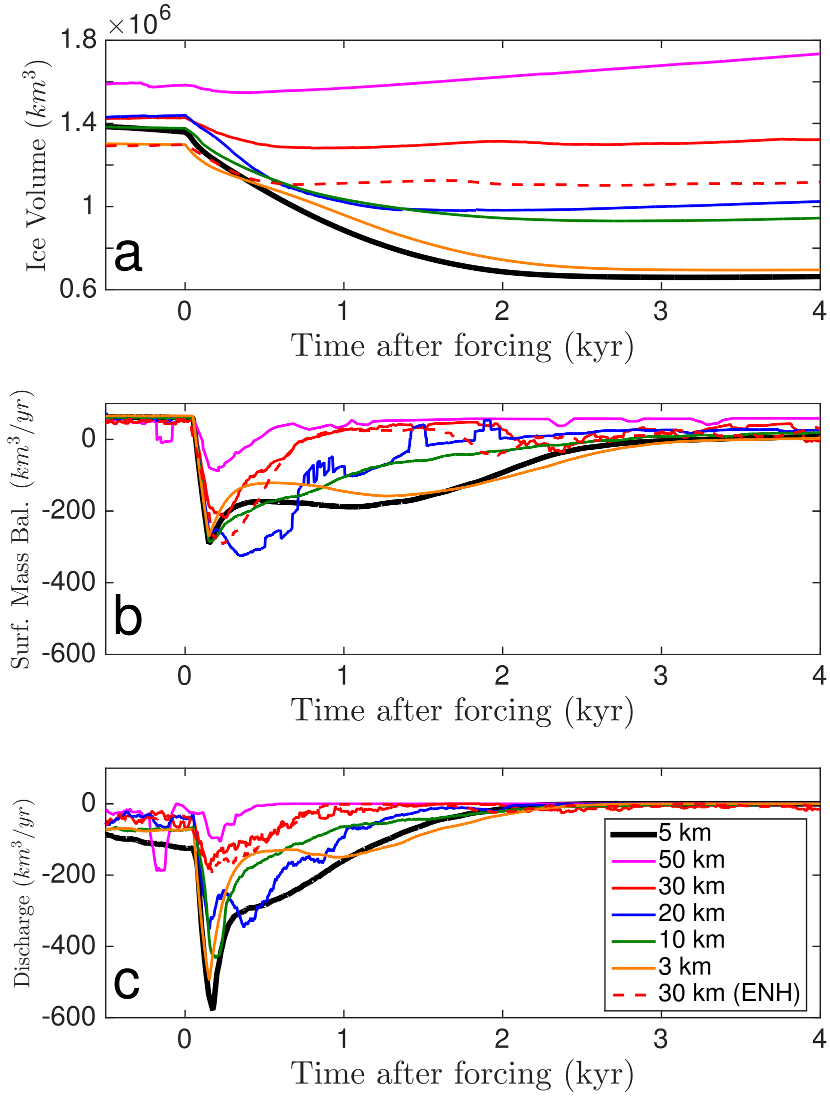

Figure S1: Ice sheet response in simulations with differing horizontal model resolution. (a) Ice volume following change in forcing. (b) Surface mass balance following change in forcing. (c) Discharge due to calving at the ice sheet margin following change in forcing. All curves in panels b and c are smoothed from raw model output to eliminate sub-centennial numerical noise.

where surface melting is confined to a narrower area. Consequently, even after an upward shift in ELA, most of the coarse, thicker ice sheet stays in the accumulation zone, resulting in a smaller decrease in surface mass balance (Figure S1c). At moderate resolution (10, 20 km; green and blue lines), there are a smaller increase in discharge following forcing, and both enhanced discharge and surface melting are not sustained for long following forcing. Additionally, the maintenance of surface melting by ice stream advection from high elevations to low elevations quickly abates in the coarsest simulations.

The highest resolution simulations (3 and 5 km; solid black and orange lines) capture a qualitatively similar rapid acceleration in ice stream discharge which produces the most rapid deglaciation following a change in climate forcing. The amount of ice volume lost during deglaciation (Figure S1a) is close in these high resolution simulations, indicating that the model is at or near convergence. It may be the case that further refinement of horizontal model resolution would change the ice stream discharge response to forcing slightly more. Indeed, previous studies have shown the necessity of resolving the grounding zone transition (Schoof, 2007a) and sharp transitions in bed strength at ice stream shear margins (Haseloff et al., 2015) at sub-kilometer resolutions. Nonetheless, by employing a basal stress interpolation scheme at the grounding line (Feldmann et al., 2014), PISM avoids significant resolution dependence below 20 km grid spacing and is broadly comparable to high resolution models in accurately simulating grounding line migration and discharge at coarse resolution. Such an approach avoids parameterizing discharge at the grounding line, which can lead to artifacts during rapid transients (such as deglaciation) and inconsistencies in the prescribed velocity and longitudinal stress at the grounding line (Pattyn et al., 2012). The extent of grounding line retreat during the early stages of deglaciation (approximately 200 km) is significantly larger than the grid spacing, lowering the potential risk associated with heavily discretized grounding line retreat. Additionally, we do not attempt to smooth transitions in bed roughness in ice stream shear margins so that we can maintain precise control over ice stream width. Though it is unlikely that the grounding line in being accurately simulated at very coarse resolutions such as 30 and 50 km, this bolsters our conclusion that the inability of coarse models to resolve ice stream discharge (whether at ice stream shear margins or the grounding line) greatly hinders their deglacial response to forcing. Rather, the purpose of these simulations is to show that at much coarser resolutions, ice sheet simulations of deglaication are subject to quite significant error due to their inability to resolve length scales similar to the ice stream width (∼10's of km) and smaller membrane coupling length scales (10 km; Hindmarsh, 2009).

A frequent problem in coarse-resolution ice sheet modeling is a mismatch between simulated ice sheet volume and proxy measurements. One common strategy to fix this problem is tuning ice flow "enhancement parameters" which take advantage of the large uncertainty in physical and chemical ice properties to modify effective ice viscosity and obtain a better fit between the modeled ice sheet and observations (as is done in the studies of Huybrechts, 1996; Tarasov and Peltier, 2004; Zweck and Huybrechts, 2005; Ganopolski et al., 2010). Our results offer a complementary perspective on the use of enhancement parameters. We suggest that differences in both the ice sheet volume during growth and the ice sheet evolution during deglaciation may be caused by the inability of the model to resolve ice stream dynamics, rather than by use of an incorrect enhancement parameter.

Figure S1a shows that different resolutions lead to a different ice sheet volume during growth and just before applying the change in climate forcing (at $t = 0$ kyr in Figure S1). Some of this difference in the simulated ice volume before forcing is due to the inability of coarse ice sheet models to resolve the mechanical grounding zone transition properly (Schoof, 2007b) and some can also be attributed to the ability of the model to resolve ice streams. Here, we contrast the use of an enhancement factor with the effect of properly resolving ice streams. To do so we tune the 40 kyr ice volume of the 30 km resolution simulation (red solid line in Figure S1a) to match the 3 km resolution simulation (orange line) by using an enhancement parameter of 2.75 both for the shallow ice and shallow shelf effective viscosities. Compared to the un-enhanced 3 km simulation, the deglaciation of the enhanced 30 km simulation (red dashed line) is always slower and results in 70% less ice volume loss over the entire deglaciation. This is due to the muted ice stream acceleration, in the enhanced 30 km simulation, which drives the rapid discharge response in the 3 km simulation (Figure S1c). Our interpretation is that using enhancement parameters introduces compensating errors, where our ability to fit the 40 kyr ice volume is due to an error in the tuned effective viscosity which compensates for errors resulting from the under-resolution of ice streams. These errors, though, stop compensating during deglaciation, leading to a difference between deglaciation in the 3 km and enhanced viscosity 30 km simulations. Although enhancement parameters can be an effective tool for modifying ice sheet volume and topography to match observations at a single point in time, they cannot at the same time effectively replicate the time-dependent ice sheet response to forcing which, as we have shown, is driven by ice stream acceleration.

2 Sensitivity of simulated deglaciation to various changes in model configuration and forcing.

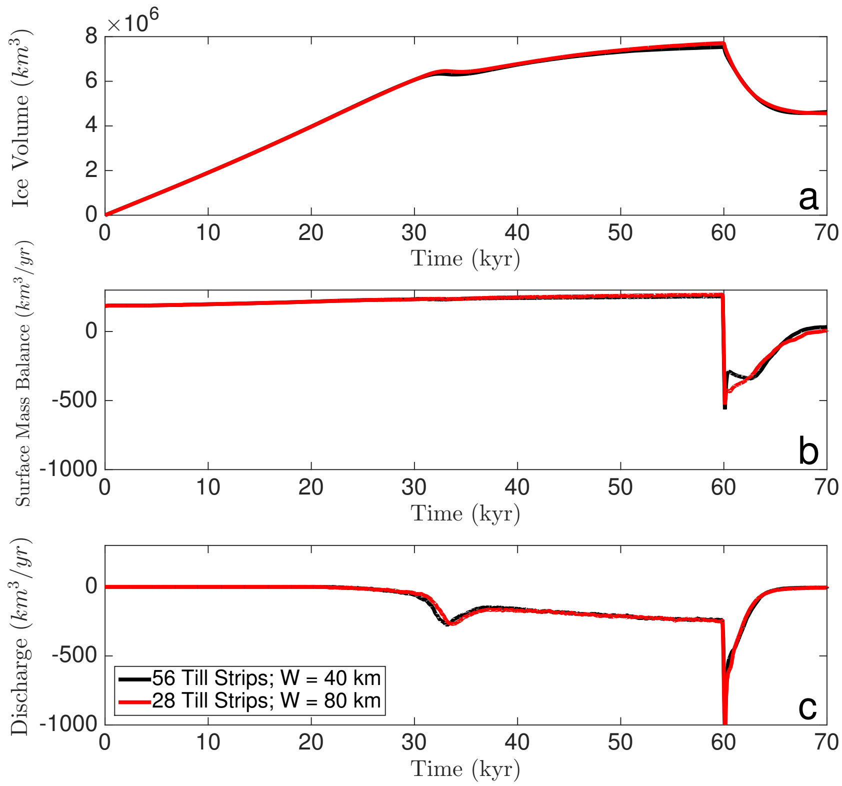

Figure S2: Sensitivity of deglacial ice sheet response to changes in till configuration. Black lines are configured with 56 weak till strips of 40 km width each (same as black line in Figure 2 of main text). Red lines are configured with 28 weak till strips of 80 km width. (a) Ice volume. (b) Surface mass balance. (c) Discharge due to calving at the ice sheet margin following.

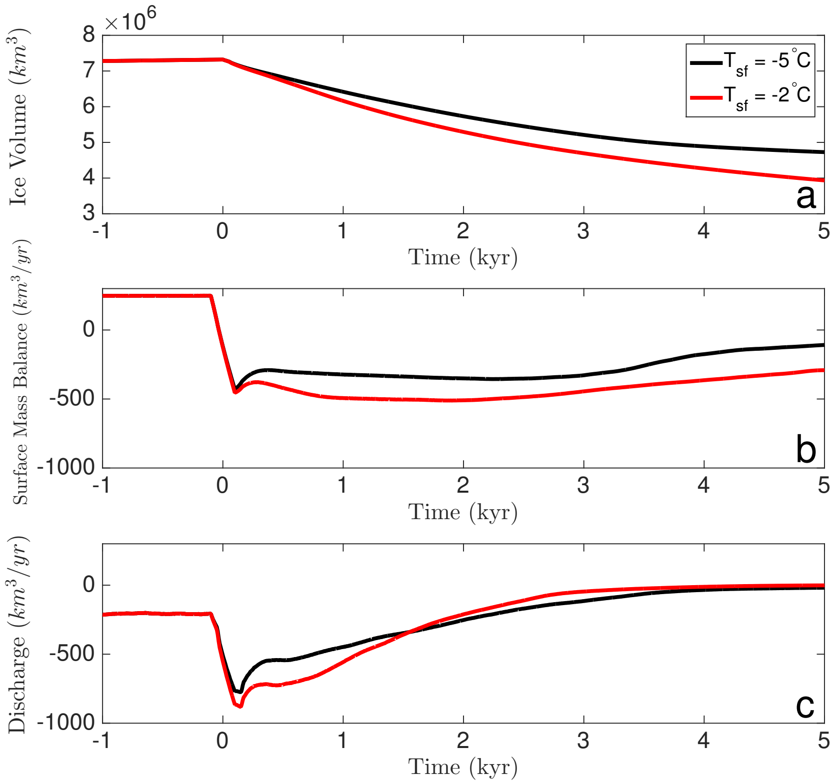

Figure S3: Sensitivity of deglacial ice sheet response to prescribed changes in sea level temperature. Black lines are configured with final $T_s = -5°C$ (same as black line in Figure 2 of main text). Red lines are configured with final $T_s = -2°C$. (a) Ice volume. (b) Surface mass balance. (c) Discharge due to calving at the ice sheet margin following.

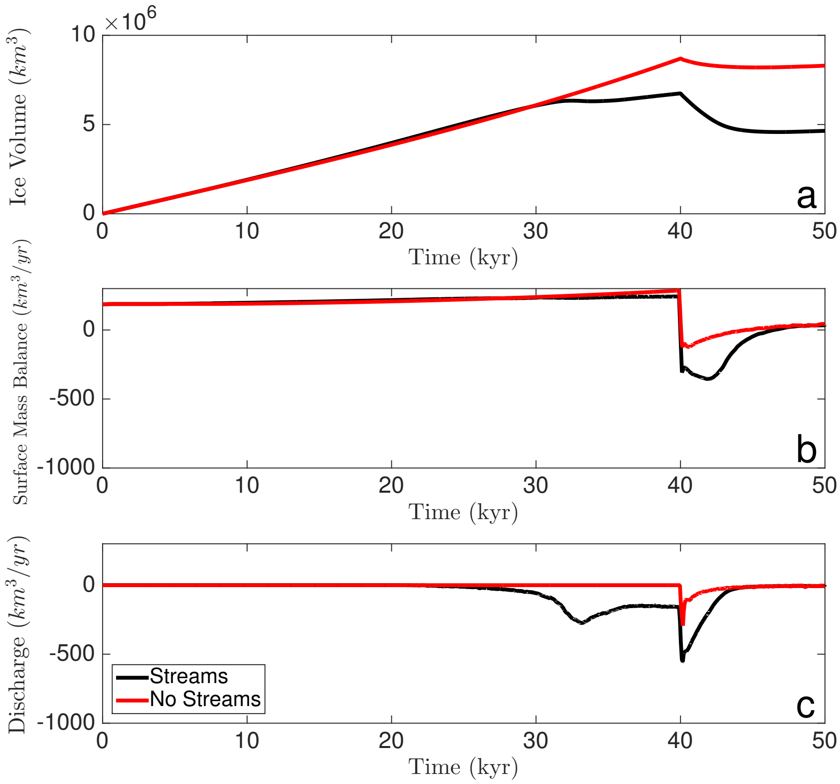

Figure S4: Sensitivity of ice sheet evolution to presence of ice streams. Black lines are configured with ice streams (same as black line in Figure 2 of main text). Red lines are configured with $\phi = 80°$ everywhere in model domain. (a) Ice volume. (b) Surface mass balance. (c) Discharge due to calving at the ice sheet margin following.

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