Melting and freezing under Antarctic ice shelves from a combination of ice-sheet modelling and observations
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Supplementary Materials

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S1. Experiments with freely evolving grounding lines and calving fronts

This document presents three additional experiments run for 500 model-years, starting from the equilibrium dynamical state of the Antarctic ice sheet and ice shelves from the REF experiment presented in the main text (Figures 1 and 2 in the manuscript). In these experiments, the grounding line and ice-shelf calving fronts are no longer fixed, and different boundary conditions are applied at the base of ice shelves. The grounding line position is now computed using a floatation condition (Sato and Greve, 2012), while calving at the ice-shelf front is parameterised using a simple threshold: if ice-shelf thickness at the front drops below 50 metres, ice within this grid cell is automatically removed (Sato and Greve, 2012). In the first simulation (henceforth PRG), the retrieved basal mass balance (BMB; Figure 1 in main text) is directly applied at the base of ice shelves in order to test whether the equilibrium state is maintained when the grounding line is released. The second simulation (henceforth MLT) uses the same set-up as PRG, but the inferred basal freezing across the ice-shelf accretion areas are neglected (set to a value of 0 m a^{-1}), to demonstrate the effects of disregarding the basal accretion processes. The third simulation (henceforth BnG) replaces the retrieved BMB for an existing parameterisation of the ice-ocean interaction in order to gauge the effects of the common simplifications of the melting and freezing patterns on the modelled ice sheet and ice shelves.

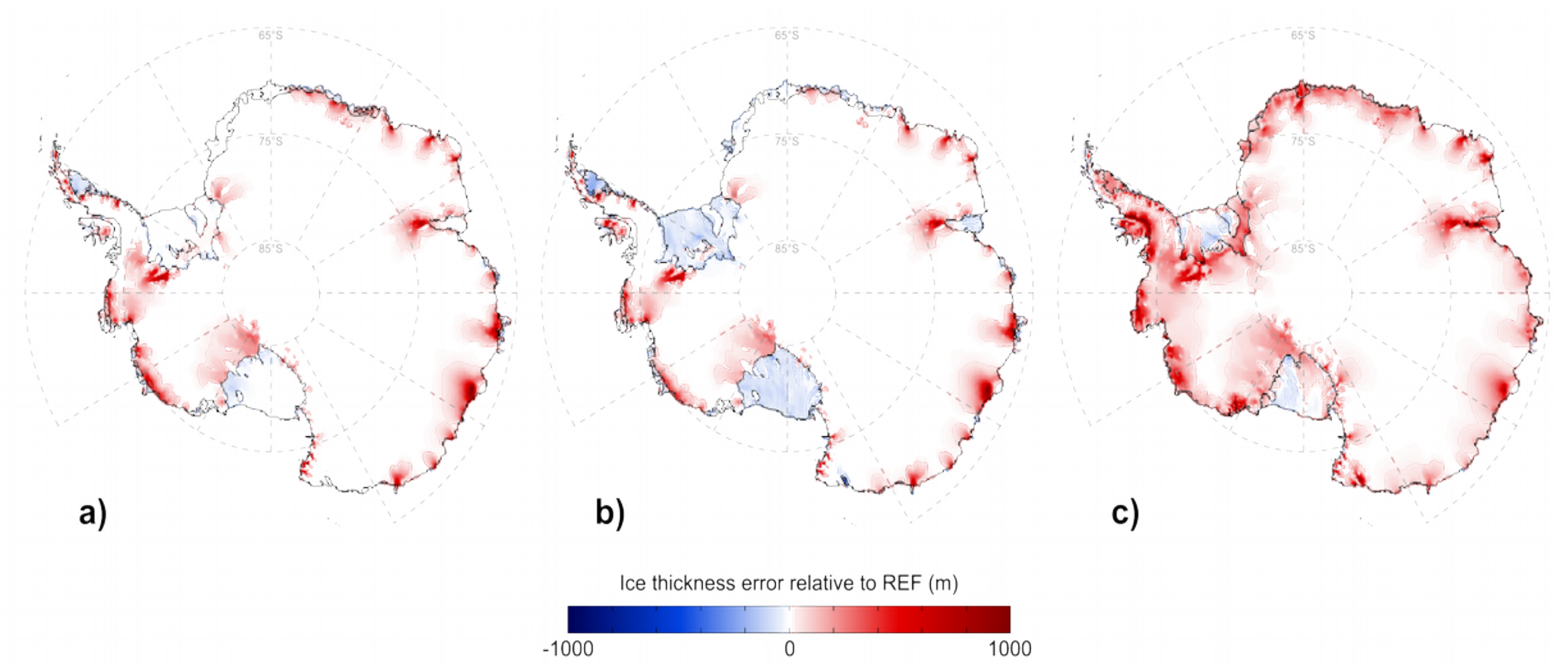

Figure S1: Ice thickness errors relative to the REF simulation, in metres, at the end of 500-year-long prognostic simulations starting from the equilibrium ice-sheet configuration shown in Figures 1 and 2 (in the main text), with freely-evolving grounding lines and calving fronts, and a) prescribed calibrated ice-shelf basal melting and freezing rates from this study; b) as in (a), but with sub-shelf freezing neglected; and c) prescribed parameterisation based on Beckmann and Goosse (2003), following the parameter choices of Martin and others (2011).

S1.1 Direct use of the inferred basal melting and freezing rates as a boundary condition at the ice shelf base

The PRG experiment results in an ice sheet configuration that is close to the REF experiment presented in the main text. Figure S1a shows the differences between the PRG and REF experiments. It can be observed that the errors in the ice sheet thickness remain nearly unchanged over most of the continental interior. However, these errors are amplified across regions where the REF simulation produces an overestimation of the ice thickness, especially in the vicinity of mountain ranges near the ice sheet margins. These areas are characterised by cold basal conditions, where basal thermal conditions do not favour sliding, and thus the calibration of the sliding coefficients has not been performed. Due to an accumulation of errors across such regions, the attained steady state is not absolute, thereby triggering the grounding line migration at the flux gates of some outlet glaciers, once the grounding line is released (e.g. Pine Island, Ross West, Totten, Amery, and Baudouin ice shelves). However, the predicted shifts in the grounding-line position in the PRG simulation are relatively minor, resulting in a realistic distribution of floating vs. grounded ice areas.

It is important to keep in mind that the prescribed sub-shelf melting and freezing rates in the PRG experiment are not further calibrated to compensate for the changes in the ice sheet-shelf geometry. Thus, as soon as the ice sheet advances, the high-melt areas predicted by REF near the grounding line are replaced by areas of lower melt rates characteristic of the ice shelf interior. This results in an amplification of the grounding-line advance. Our retrieved ice-shelf BMB estimates are purely diagnostic and are not meant to be used directly as a boundary condition in transient, prognostic simulations. Instead, the BMB patterns and relative magnitudes for different ice shelves could be used to aid the development of new techniques (such as parameterisations) that would allow a prognostic BMB calculation. Knowing beforehand what BMB is necessary to maintain the ice sheet in a certain dynamical state (even if the grounding line is fixed) can provide a first-order approximation that can be later fine-tuned based on the specifics of a modelling study.

S1.2 Effects of disregarding basal freezing

The results from MLT experiment are very similar to those from the PRG simulation. The main difference is that the largest ice shelves now exhibit a significant ice thickness deficit (Figure S1b) in response to a step change in the boundary conditions. Such ice thickness underestimations are not restricted to the original accretion zones predicted by the REF simulation, but instead spread over the entire ice-shelf area. If the calibration procedure were originally designed with an assumption of non basal freezing, it would compensate for this ice thickness deficit through adjustments (reduction) of melting rates elsewhere. However, the ice-shelf thickness deficit would likely remain in the accretion zones, which may deliver an unrealistic mass flux input to an ice-shelf calving model component in large-scale, long-term ice-sheet simulations, thereby potentially accelerating the collapses of portions of ice shelves.

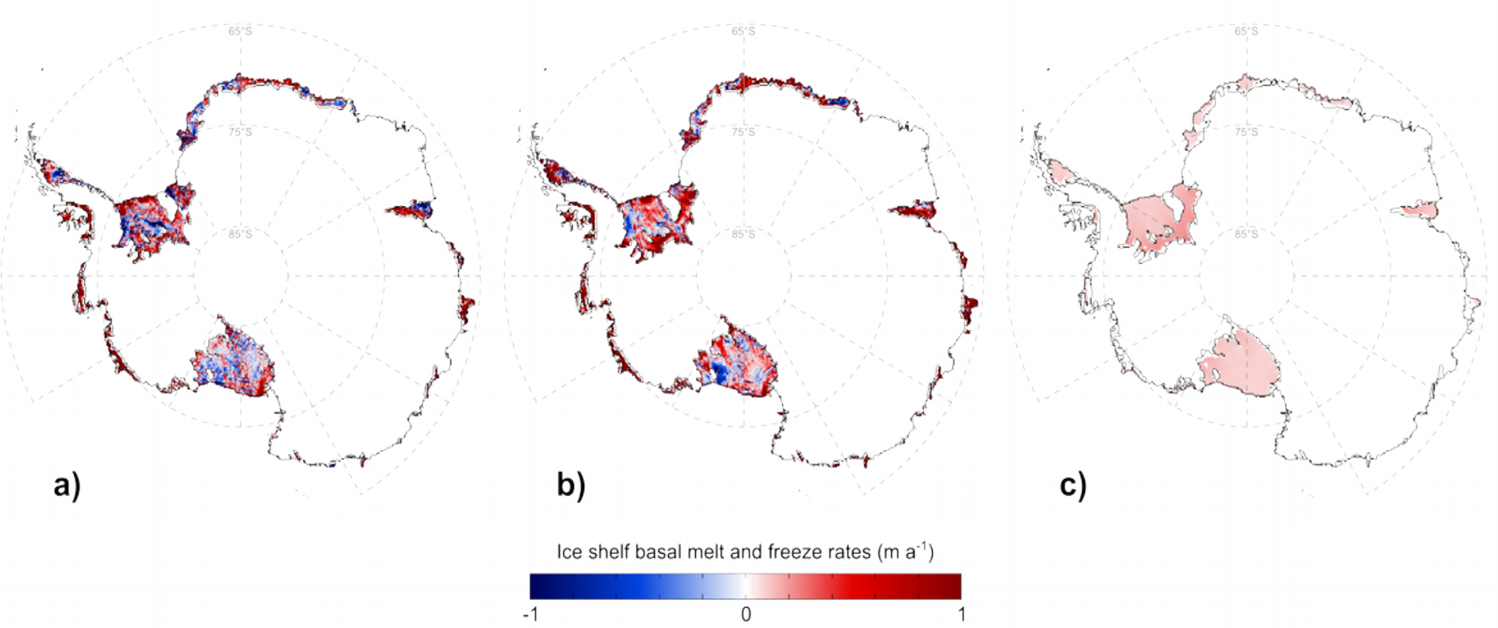

Figure S2: Ice shelf basal melting and freezing rates (in metres per year). a) Observation-based estimates of Rignot and others (2013). b) This study (as in Figure 1, in main text). c) Computed using the calibrated ice sheet from this study and a parameterisation based on Beckmann and Goosse (2003), following the parameter choices of Martin and others (2011).

S1.3 Comparison between the retrieved BMB and a standard parameterisation of ice-ocean interaction

In the BnG experiment, we have replaced the inferred basal melting and freezing rates by the parameterisation of Beckmann and Goosse (2003). The BnG experiment employs the same parameter choices as in the dynamic equilibrium simulation of Martin and others (2011), with an ocean salinity set to 35 psu, an ocean temperature of -1.7 °C, and a model parameter F_melt = 5×10^{-3} m s^{-1} (see their Eq. 5). However, an important difference is that, in our study, the distribution of basal sliding coefficients in the grounded ice sheet sectors is calibrated to minimise the misfit between the modelled and observed ice sheet thickness, thus producing different modelled ice velocities and ice fluxes across the grounding line.

The resulting sub-shelf basal melting rates from the parameterisation of Beckmann and Goosse (2003) at the beginning of the transient experiment are shown in Figure S2c, together with the observation-based distribution of Rignot and others (2013) and the inferred distribution from our study included for comparison (Figures S2a and b, respectively). The two main characteristics of the parameterised distribution of the ice shelf BMB is the lack of basal freezing and the large discrepancies with the observation-based estimates of Rignot and others (2013). In this parameterisation, the melt rates are proportional to the current depth of an ice shelf, which defines its local pressure melting point. Since the deepest parts of the Antarctic ice shelves are usually located near grounding lines, this formulation generates slightly higher melt rates in these zones, in qualitative agreement with observations (e.g. Rignot and Jacobs, 2002). However, the parameterised melt rates near grounding lines are significantly lower than the observed values. Other parameter choices can in principle be used to increase the melt rates near the grounding line, but this would also generate higher melt rates across the entire ice shelf, leading to a strong ice shelf thinning and thus an ice shelf calving.

At the end of the 500-year-long simulation, the BnG experiment results in a strong degradation of the ice sheet geometry, including the grounded ice-sheet margins, and a significant grounding-line migration in many ice sheet sectors (Figure S1c). As mentioned above, this can be attributed to the low melting rates (relative to the PRG experiment) near grounding lines, which are not sufficient to compensate for the high ice flux generated by the iterative calibration of basal sliding coefficients. Different parameter choices were tested in an attempt to reproduce the results of the PRG experiment (not shown), albeit with no success. The degradation observed in the BnG experiment indicates that this parameterisation is rather far from what our modelled ice sheet would need to keep the sheet-shelf system in an equilibrium state. Given the uncertainty in the ice sheet subglacial conditions, it may be possible to calibrate the basal sliding coefficients to obtain a realistic geometry of the modelled steady-state ice sheet using the parameterised BMB (as an independent boundary condition), but we expect that the results of such calibration will contain a significant error-compensation for the limitations described above, in addition to widespread discrepancies between the modelled and observed ice shelf geometries. In contrast, our modelled ice sheet has been actively tuned to produce the best possible ice sheet geometry that our model can generate, keeping the ice shelf geometries close to observations throughout the simulation. Thus, the ice sheet calibration is largely independent of the inferred ice shelf BMB, to which we attribute the good fit between our BMB estimates and observations.

Supplementary references

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