Dynamics of the last glacial maximum Antarctic ice-sheet and its response to ocean forcing

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Retreat of the Last Glacial Maximum (LGM) Antarctic ice sheet is thought to have been initiated by changes in ocean heat and eustatic sea level propagated from the Northern Hemisphere (NH) as northern ice sheets melted under rising atmospheric temperatures. The extent to which spatial variability in ice dynamics may have modulated the resultant pattern and timing of decay of the Antarctic ice sheet has so far received little attention, however, despite the growing recognition that dynamic effects account for a sizeable proportion of mass-balance changes observed in modern ice sheets. Here we use a 5-km resolution whole-continent numerical ice-sheet model to assess whether differences in the mechanisms governing ice sheet flow could account for discrepancies between geochronological studies in different parts of the continent. We first simulate the geometry and flow characteristics of an equilibrium LGM ice sheet, using pan-Antarctic terrestrial and marine geological data for constraint, then perturb the system with sea level and ocean heat flux increases to investigate ice-sheet vulnerability. Our results identify that fast-flowing glaciers in the eastern Weddell Sea, the Amundsen Sea, central Ross Sea, and in the Amery Trough respond most rapidly to ocean forcings, in agreement with empirical data. Most significantly, we find that although ocean warming and sea-level rise bring about mainly localized glacier acceleration, concomitant drawdown of ice from neighboring areas leads to widespread thinning of entire glacier catchments—a discovery that has important ramifications for the dynamic changes presently being observed in modern ice sheets.

deglaciation | ice-sheet modeling | longitudinal coupling | enhanced flow

Transitions between stable states of polar ice sheets are likely governed by thresholds, with rapid changes taking place during perturbation from one condition to the other (1). Establishing the rate at which such changes proceed, and the mechanisms that drive such transformations, commonly relies on geological data from previous glacial-interglacial transitions. Recent research suggests that previous interglacials may have brought about the repeated collapse of marine sectors of Antarctica (2, 3), with evidence from both hemispheres now indicating a dominant oceanic-forcing role in ice-sheet behavior both at present and in the recent past (4, 5). Yet geochronological records of the last glacial termination in Antarctica are ambiguous, with apparently contradictory records indicating either early (*ca.* 19–16 ka) or late (<15 ka) retreat in different sectors (6–9), making it difficult to confidently infer the mechanisms which initiated and drove Antarctic deglaciation, or even to establish whether the southern hemisphere ice sheet receded synchronously with ice sheets in the north. Differences in the pattern and timing of LGM ice-sheet retreat in different sectors of Antarctica have been suggested to have arisen from either gravitationally induced regional variability of sea-level changes (10) or the stabilizing effects of grounding-zone sediment wedges (11), but these theories have yet to be verified against dated margin retreat positions at a continental scale. Here we propose and investigate a third possibility—that differences in the mechanism of ice-sheet flow played a critical role in controlling the rate and locations of ice-margin recession

by governing the way that the ice sheet responded to deglacial sea-level rise and ocean warming.

Recent advances in our understanding of modern Antarctic ice-sheet dynamics indicate that a significant component of motion arises from enhanced flow—that is, movement as a consequence of basal sliding as well as internal deformation, even far into the interior (12). For paleoglaciological studies, the importance of these findings lies in the behaviors that arise from these different processes. An ice sheet flowing through viscous deformation alone cannot respond to environmental perturbations as rapidly, or as widely, as one whose motion comes from basal sliding and is controlled (at least in part) by longitudinal coupling (13, 14). In the context of Antarctic ice-sheet deglaciation, ocean forcings will therefore only bring about rapid and significant changes if the responding ice sheet is able to quickly propagate the changes taking place at the oceanic boundary further inland (15). In ice shelves and ice streams, where membrane stresses are dominant (16), flow perturbations are transmitted quickly along conduits of enhanced flow, and changes at marine margins are conveyed inland very effectively (14, 17). Where basal sliding is absent, this connectivity is orders-of-magnitude slower. Furthermore, the impact of external forcings on overall ice-sheet mass balance will also depend on the magnitude of horizontal ice flux (*i.e.*, discharge). Because both velocity and discharge vary spatially, response of an ice sheet to far-field perturbations will be highly variable, even between neighboring catchments, and the lag between oceanic perturbations and their manifestation in geological archives far inland will depend on the proximity of sites to zones of enhanced flow (9).

Here we use a sophisticated ice-sheet model to simulate the geometry and dynamics of the LGM Antarctic ice sheet to (i) identify ice-sheet sectors dominated by enhanced ice flow, (ii) predict the response of this ice sheet to sea-level rise and ocean warming, and (iii) assess how these predictions compare to geological evidence of Antarctic deglaciation.

Results and Discussion

Geological data provide essential constraints to our ice-sheet modeling experiments. Pan-Antarctic cosmogenic surface exposure ages from bedrock samples and glacial erratics indicate that ice thicknesses close to the present coast were several hundred meters greater during the LGM than at present, and tapered inland (*SI Appendix, Table S1*), in agreement with inferences from ice cores (18). This terrestrial record constrains the vertical dimensions of the former ice sheet, whereas marine geologic

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Fig. 4. (A) Response of ice-sheet thickness (ΔH) and velocity (Δu) after 1,000 y of an isochronous 25 m rise in sea level from the LGM lowstand, and (B) ice-sheet response when the same sea-level rise is accompanied by a stepped increase in oceanic heat flux of one-third the difference between present and LGM values as prescribed in our model. Grounded ice only is shown; ice shelves are modeled but omitted from display for clarity. Modeled grounding line at maximum LGM extent (gray dotted line) shown to highlight areas of recession. Coastal thickening of 10–20 m occurs in stable-margin areas as a consequence of slow diffusion of ice from inland areas. Oblique illumination (gray shading) is used to highlight areas of greater surface slope (Left) and steeper velocity gradients (Right).

Further experimentation may also help to determine whether the deglacial behavior of an LGM ice sheet that was out of equilibrium, continually adjusting to time-transgressive changes in ocean temperature, sea-level, and atmospheric conditions, would be the same as that of our steady-state ice sheet. If the LGM ice sheet were still expanding when deglaciation began, for example, it may have taken longer to respond to negative mass balance at the margin than an ice sheet that was already retreating, perhaps leading to delayed retreat in some areas. Nonetheless, in our steady-state experiments we find that the rate of grounding-line migration is controlled by the magnitude of the imposed forcings, whereas the regional pattern of ice margin retreat depends on the rate and volume of ice discharge from inland areas, the presence of pinning points, and the bathymetry of the embayments where ice loss takes place. Thus we infer that an indented margin characterized by calving bays that were fed by fast-flowing conduits, as predicted by our model in embayments such as the Ross Sea, is likely representative of the morphology of the retreating LGM ice-sheet margin, irrespective of whether deglaciation initiated from an equilibrium configuration or not.

Conclusions

By using an empirically constrained high-resolution ice-sheet model to simulate the Antarctic ice sheet at the LGM, and by forcing this model with oceanic perturbations, we conclude that spatial contrasts in Antarctic ice-sheet dynamics played a more important role in modulating southern hemisphere ice-sheet sensitivity to ocean forcings than previously realized, and may

explain patterns of retreat not otherwise accounted for by regional enhancement of sea levels or grounding-line stabilization from sediment accumulation. That widespread ice-sheet thinning arises from localized acceleration of ice streams is particularly significant when considering recent observations of velocity increases in both Antarctic and Greenland ice sheets (35).

Materials and Methods

We use a three-dimensional, thermomechanical, continental ice-sheet model constrained by geological data that define lateral and vertical extents of the expanded Antarctic ice sheets around the time of the LGM. As in previous studies, we employ boundary distributions from modified BEDMAP topography (36), temperature and precipitation fields from gridded datasets (37, 38), and a spatially varying geothermal heat flux interpolation (39). Our model computes ice thickness and temperature changes, isostatic depression of topography, migration of grounding lines, and the growth of ice shelves. Interaction between modeled ice shelves and their surrounding ocean is accounted for using a mass balance determination based on heat flux across the ice-water boundary. We employ a stress balance that includes longitudinal (membrane) stresses ([SI Appendix, Materials and Methods](#)), impose boundary conditions (sea-level lowering, precipitation reduction, and atmospheric temperature perturbations) representative of the LGM, based on ice and marine sediment core isotopic deviations (40, 41) ([SI Appendix, Fig. S5](#)), and adjust model parameters affecting bed traction, ice rheology, and ice-shelf mass balance. In contrast to other studies (42), however, the geometry and dynamics of our modeled ice sheet are able to evolve naturally, because we do not prescribe grounding line or ice stream locations. Furthermore, we make use of parallel processing to implement our model at a uniquely high (5 km) resolution, achieving a 16–64 times increase in detail compared to other Antarctic simulations (27, 42, 43).

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