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The influence of continental shelf bathymetry on Antarctic Ice Sheet response to climate forcing

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ABSTRACT

We investigated whether shelf-depth changes would have influenced Antarctic Ice Sheet (AIS) response to climate forcing using the Parallel Ice Sheet Model (PISM). The simulations confirm that this would have indeed been the case. For the last-glacial-cycle (LGC) type forcing we prescribed, a modern-like polar AIS surrounded by shallow and intermediate bathymetries experiences rapid grounding-line advance early during the transition from interglacial to glacial forcing. This is in contrast to our baseline simulation of AIS response on the currently overdeepened bathymetry, which showed the expected gradual advance of grounding lines to the same climatic forcing. In the simulation, the more-positive mass balance for the shallower bathymetry is primarily a result of significantly lower calving fluxes from smaller-area ice shelves. On the basis of these results, we suggest that shelf bathymetry is an important boundary condition that should be considered when reconstructing AIS behavior since at least the middle Miocene. We note that caution should be used when applying these concepts because the particular way in which AIS mass balance is altered by shelf depth depends on how the changes in accumulation and ablation at the marine terminations combine with accumulation and ablation on land.

1. Introduction

Ice-sheet mass balance is the sum of accumulation and ablation both on land and at the marine terminations. In the Antarctic, snowfall accumulation is typically low because the air is very cold and dry (e.g., Bromwich, 1988), although precipitation rates exceeding 1 ma^{-1} occur in the Antarctic Peninsula (Lenaerts et al., 2012). Ice is also added by freeze-on to the underside of ice shelves at the ice sheet's marine margins (Schoof, 2007). The existence of accumulation by sub-ice-shelf freeze-on depends on ice and ocean temperatures. Ablation by melting at the ice-sheet surface is negligible over most of the AIS (Vaughan, 2006) with the exception of the some northern parts of the Antarctic Peninsula where significant surface melting occurs (Cape et al., 2015). Surface ablation by sublimation can be an important component of local mass balance in some areas, such as McMurdo Sound (McCrae, 1984). Significant ablation also occurs by calving of icebergs from ice shelves (Depoorter et al., 2013). Ablation by melting from the underside of the ice shelf occurs where relatively warm ocean water is in contact with the underside of ice shelves (Rignot and Jacobs, 2002; Rignot et al., 2013; Liu et al., 2015).

In the current interglacial, mass balance for the entire AIS is slightly positive (Zwally et al., 2015) although some parts of the West Antarctic Ice Sheet (WAIS) are experiencing negative mass balance (e.g., Rignot and Thomas, 2002; Velicogna and Wahr, 2006). The potential for high-volumes fluxes of either marine ablation (sub-ice-shelf melt-off) and/or accumulation (sub-ice-shelf freeze-on) exists because the area of the marine termination is extremely large on the overdeepened continental shelf. Moreover, since the seafloor is foredeepened, i.e., the marine surface slopes inland, the vertical dimension of the ice-ocean contact area increases as grounding lines retreat from the shallower shelf-edge sill. Many previous studies have noted the inherent instability of the AISs associated with the reverse gradient of the shelves (e.g., Thomas, 1976; Hughes, 1977) during transitions from glacial to interglacial climate states as the grounding line retreats into deeper waters on the inner shelf. The geologic evidence of ice-sheet retreat from the continental shelves demonstrates that an average condition of negative mass balance has existed for most of the time since the end of the last glacial maximum (LGM).

For those time intervals when the continental shelf was shallower, the ice/ocean contact areas would have been smaller. Hence, the maximum possible contributions of ice shelf processes (e.g., iceberg calving and sub-ice-shelf melting/freezing) to ice-sheet mass balance would have been reduced in comparison to that which otherwise occurs for similar conditions of an ice sheet terminating on an overdeepened bathymetry. The purpose of our study was to investigate the question of whether shelf-depth changes through geologic time might have affected AIS dynamics. In this paper, we use AIS dynamics to refer to

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the rates and timing of grounding-line migration and ice volume changes during a climate cycle. Here we use PISM simulations to demonstrate that changes to shelf depth should be considered when reconstructing and/or modeling AIS history from proxy and direct data. In our simulations of shallow and intermediate-depth bathymetries, the differences in AIS response primarily resulted from lower ablation by iceberg calving.

2. Background

2.1. On characteristics, causes and significance of Antarctica's overdeepened passive margin

Antarctica is near completely surrounded by passive margins that began forming in the Mesozoic from the breakup of Pangea. However, in contrasts to passive margins of similar age, its morphology is very different. Antarctica's deep shelves are crossed by glacially-eroded troughs (Shepard, 1931). Broad banks rise to above 200 m water depth between troughs. The average shelf depth is 500 m (Johnson et al., 1982), which is considerable deeper than the ~120-m world average (Shepard, 1973). The inner shelf is foredeepened, in places reaching depths greater than 1000 m where the entire sedimentary cover has been stripped away by repeated advances of grounded ice (Bart and Anderson, 1995). The depositional and erosional features produced during the LGM are still evident at the seafloor because the continental shelf is essentially sediment starved. The East Antarctic shelves are relatively narrow whereas the West Antarctic shelves are broad with large portions covered by grounded and/or floating ice of the WAIS.

In general, passive-margin shelf depth is a result of long-term thermal subsidence and sedimentation that post-dates rifting and drift by seafloor spreading. The shelf depth is graded to sea-level elevation and isostatically adjusted to deposition and erosion. Unlike other passive margins of similar age that drifted north, Antarctica has continuously occupied a polar position since the onset of rifting ~175 Ma ago. For the majority of the time since, these high-latitude Antarctic margins were probably shallow, seaward-dipping shelves. Long-term climate cooling over tens of millions of years of the early Cenozoic eventually led to the development of ice sheets and a shift from a Greenhouse to a Icehouse World. The ice volumes would have first depressed land areas and then progressively influenced the depth of the adjacent continental shelves by glacial isostatic adjustments (GIA) and glacial erosion (ten Brink and Cooper, 1992). Isolated ice caps from upland areas would have eventually extended to lower altitudes and coalesced to form the thick ice sheets that now cover more than 99% of the continent and also have extensive marine terminations on the adjacent continental shelves.

During these long-term transitions to the icehouse world, there must have been considerable modification of the land- and marine-scape of Antarctica (Abreu and Anderson, 1998; Anderson, 1999). Some of current foredeepened topography and great depth of the Antarctic margins is indeed attributed to GIA (Drewry, 1983). The magnitude of isostatic depression varies from just under 1 km beneath the central portions of the East Antarctic Ice Sheet (EAIS) to 0.5 km beneath the central parts of the WAIS. According to Drewry (1983), the continental shelves of East Antarctica are isostatically depressed ~150 m near the grounding line in places where the EAIS profile is steepest. The proglacial isostatic depression below a full-bodied ice sheet extends more than 180 km seaward of the grounding line.

The overdeepened and foredeepened nature of the continental shelf is also due to glacial erosion (Anderson, 1991; ten Brink and Cooper, 1992). Truncation at broad cross-cutting unconformities seen on seismic data demonstrate the grounded ice has eroded the continental shelf on multiple occasions since ice sheets first reached sea level (Houtz and Davey, 1970; Larter and Barker, 1989; Cooper et al., 1988; Anderson and Bartek, 1992; Eittreim et al., 1995; Bart and Anderson, 1995; Bart et al., 2011). Hayes and Davey (1975) estimated that more than 800 m of strata were removed from the Ross Sea inner shelf. GIA is difficult to isolate from the effects of glacial erosion even in the modern situation when the ice thicknesses can be measured. It is important to keep in mind that erosion, like deglaciation, triggers isostatic rebound. In other words, 800 m of stratal erosion accomplished over several glacial cycles would produce some smaller increase in shelf depth because the continental shelf rebounds isostatically. Nonetheless, megascale lineations and other subglacial features at the seafloor demonstrate that erosion was widespread across the continental shelf during the LGM.

The overdeepened shelf is an important physical condition of the global climate system. The deepest and coldest ocean waters are formed on Antarctic shelves. Repeat satellite mapping surveys have shown that the ice-sheet mass balance near the marine terminations is shifting towards negative due to the melting by warm CPDW that intrudes onto the shelf. These are important sites of heat exchange between the ocean and the cryosphere. Shelf depth and its evolution through time may have influenced the location and volume of warm-water intrusion (e.g., Jacobs et al., 2012; Bart and Iwai, 2012). As noted earlier, the shelf depth and configuration controls the area of contact between the ocean and the ice sheet, whether or not the area of the ice shelves change through time as the grounding line migrates back and forth through glacial cycles. Hence, the physical boundary condition of the Antarctic shelf depth is an important factor that controls how the marine termination of the AIS interacts with other ocean-centric aspects of the climate system.

2.2. Likely time intervals of Antarctic shelf depth change

In earlier intervals of geologic time, the Antarctic land and marine scape were likely to have been very different than today (Abreu and Anderson, 1998; Wilson et al., 2013). It is not yet possible to confidently say when or even if shallow bathymetry co-existed with an AIS of a particular extent, thickness and thermal character primarily because the Antarctic shelf-depth changes through time are not well constrained by direct evidence. This is partly because there are few drill sites on the Antarctic shelves. Given the relationship of GIA and glacial erosion to the current overdeepened shelf, it is reasonable to assume that Antarctic shelf depths changed in association with the glacial history of the continent. Much detailed information about the AIS history is interpreted from high-resolution deep-sea proxy evidence and low-resolution sea-level records. These data provide constraints on when ice sheets should have created GIAs of adjacent continental shelf but they do not provide information as to where the ice volumes were located.

Ice caps may have existed on Antarctica during the late Cretaceous and early Paleogene (Frakes and Francis, 1988; Miller et al., 2005). These ice caps would have been confined to isolated upland areas and so may not have reached sea level except during extreme glacials. The early Oligocene ice-volume expansion (Zachos et al., 1994, 2008) probably coincided with significant isostatic depression of the land. Ice volumes in the early to late Oligocene may have oscillated from 60 to 130% of the modern AIS volume (Zachos et al., 1994). If so, isostatic depression on the land would have occurred. A second major episode of GIA may have occurred until much later, during the Middle Miocene Shift (MMS; from ~14.5–12.5 Ma) as glaciation intensified in a series of steps (Shackleton and Kennett, 1975; Flower and Kennett, 1995). By ~14.0 Ma, the Antarctic climate had shifted from temperate to polar (Lewis et al., 2008). Early Pliocene deglaciation probably produced a significant isostatic rebound of West Antarctic margins and interiors. Conversely, the smaller-scale waxing and waning on the outer shelves probably would have induced relatively minor GIA (Golledge et al., 2012).

Direct evidence of truncation at broad, concave glacial erosion surfaces on the Antarctic continental shelf is seen on seismic profile that cross the shelf (e.g., Bartek and Anderson, 1991; Henrys et al.,