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Potential Antarctic Ice Sheet retreat driven by hydrofracturing and ice cliff failure

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ABSTRACT

Geological data indicate that global mean sea level has fluctuated on 10^3 to 10^6 yr time scales during the last ∼25 million years, at times reaching 20 m or more above modern. If correct, this implies substantial variations in the size of the East Antarctic Ice Sheet (EAIS). However, most climate and ice sheet models have not been able to simulate significant EAIS retreat from continental size, given that atmospheric CO_2 levels were relatively low throughout this period. Here, we use a continental ice sheet model to show that mechanisms based on recent observations and analysis have the potential to resolve this model–data conflict. In response to atmospheric and ocean temperatures typical of past warm periods, floating ice shelves may be drastically reduced or removed completely by increased oceanic melting, and by hydrofracturing due to surface melt draining into crevasses. Ice at deep grounding lines may be weakened by hydrofracturing and reduced buttressing, and may fail structurally if stresses exceed the ice yield strength, producing rapid retreat. Incorporating these mechanisms in our ice-sheet model accelerates the expected collapse of the West Antarctic Ice Sheet to decadal time scales, and also causes retreat into major East Antarctic subglacial basins, producing ∼17 m global sea-level rise within a few thousand years. The mechanisms are highly parameterized and should be tested by further process studies. But if accurate, they offer one explanation for past sea-level high stands, and suggest that Antarctica may be more vulnerable to warm climates than in most previous studies.

1. Introduction

Studies of sea-level variations over the last ∼25 million years include geochemical and faunal analysis of ocean core records, and paleo-shoreline indicators, indicating quite high stands at some times (Miller et al., 2012; Foster and Rohling, 2013; Naish and Wilson, 2009; Raymo and Mitrovica, 2012). There is some uncertainty about how much their high-stand values are distorted regionally by glacial isostatic adjustment and dynamic topography (Rowley et al., 2013; Rovere et al., 2014). Here we assume that some of them do represent eustatic high stands at least 20 m above modern, which could only have been caused by ice loss from Greenland and Antarctica.

Most of the West Antarctic Ice Sheet (WAIS) is grounded well below sea level, with extensive grounding lines and wide ice shelves directly in contact with the ocean. Models and data indicate this ice is vulnerable to ocean warming, and has probably collapsed and recovered multiple times in the past (Vaughan, 2008; Naish et al., 2009). Increased oceanic melting at the base of floating ice shelves causes thinning and reduces their buttressing effect (back stress) on interior ice, and if the bed deepens upstream, this can lead to runaway retreat due to the very strong dependence of ice flux on grounding-line depth – termed "Marine Ice Sheet Instability" (MISI) (Weertman, 1974; Mercer, 1978; Schoof, 2007). However, the contribution of a complete marine WAIS collapse to global sea level is only ∼3.3 m above modern (Bamber et al., 2009). The Greenland Ice Sheet, after its first full growth probably in the Pliocene, also diminished considerably during past warm interglacial periods (mainly by surface melting due to its lower latitudes), but contributed perhaps as little as ∼2 m to global sea level during the last interglacial (Dahl-Jensen et al., 2013), and at most ∼7.3 m if complete collapse occurred during earlier warm times (Alley et al., 2010). Together, WAIS and later Greenland have contributed at most ∼3 to 10 m, so past sea-level variations of 20 m or more above modern require East Antarctic contributions of at least 10 to 17 mesl (meters equivalent sea level), ∼20 to 30% of its modern volume.

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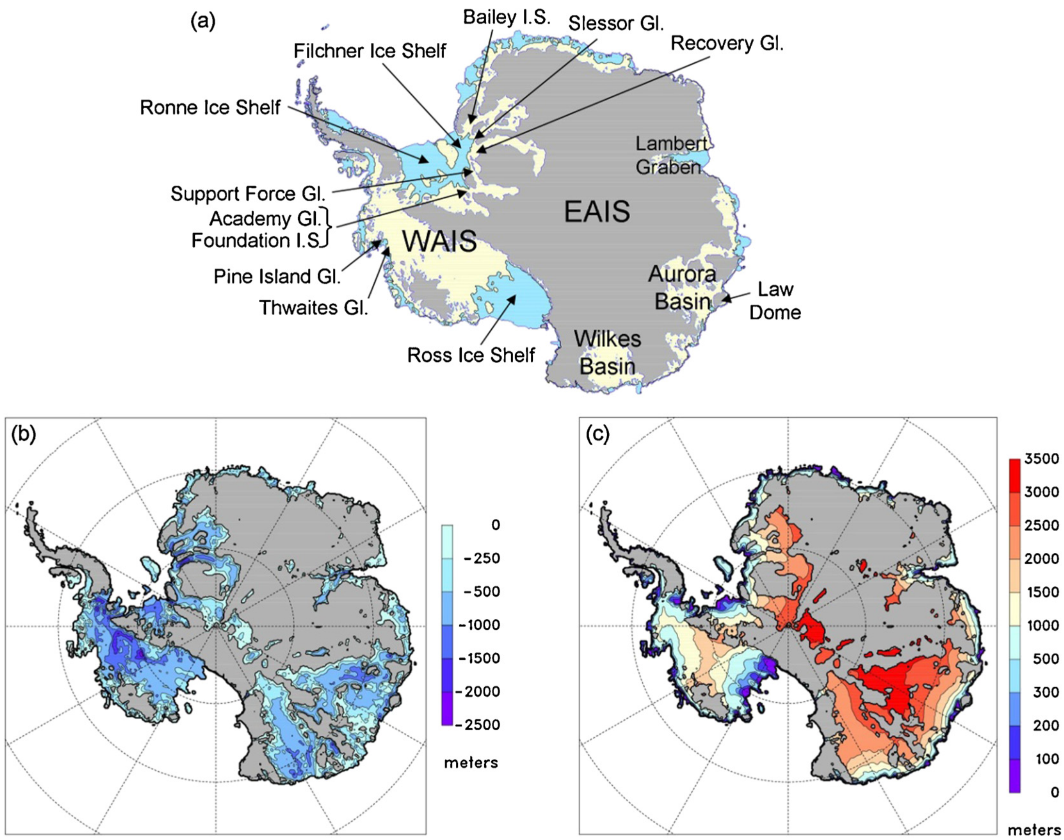

Fig. 1. Antarctic location map and modern properties. (a) Locations of features named in the text. EAIS = East Antarctic Ice Sheet, WAIS = West Antarctic Ice Sheet, I.S. = ice stream, Gl. = glacier. Yellow shading shows the areas of grounding line retreat after 5000 yr in the main retreat simulation of Fig. 3, and cyan areas are modern floating ice shelves. (b) Modern bedrock elevations that are below sea level. (c) Modern ice thickness above flotation, i.e., $h_i - (\rho_w/\rho_i)(S - h_b)$ where h_i is ice thickness, h_b is bed elevation, S is sea level, and $\rho_w/\rho_i = 1028/910$ is the ratio of ocean to ice densities used in the model. h_i and h_b are regridded to 10 km from the Bedmap2 dataset (Fretwell et al., 2013). Values are shown only for ice grounded below sea level (where $h_b < S$), highlighting the volume of ice that effectively contributes to sea level rise if melted, *and* is potentially vulnerable to cliff-failure attack. The much greater values in East Antarctica compared to West explain why the EAIS contribution to sea-level rise in our simulations is larger, despite its similar area of collapse to WAIS.

In contrast to WAIS, most of the EAIS is grounded above sea level and is not directly vulnerable to ocean warming. The EAIS first attained full continental size at the Eocene–Oligocene boundary (Pusz et al., 2011; DeConto and Pollard, 2003). The atmospheric warming necessary to produce substantial retreat from continental size in previous ice-climate model simulations is considerable, ∼15 to 20 °C (Huybrechts, 1993) or atmospheric CO_2 levels of ∼4× to 9× PAL (Preindustrial Atmospheric Level, 280 ppmv) (Pollard and DeConto, 2005). Higher-resolution climate model simulations with ∼2× PAL CO_2 predict very little surface melting of East Antarctica except on narrow strips around the margins, and no overall retreat; in fact, the EAIS volume *increases* due to greater snowfall in the warmer atmosphere for CO_2 up to 2× PAL (Vizcaino et al., 2010; Ligtenberg et al., 2013). This behavior is well understood, and stems from hysteresis between climate and equilibrium Antarctic ice sheet size, with the steep ice-sheet flanks and atmospheric lapse rate protecting most of the surface from warming summer temperatures (Height–Mass-Balance Feedback; Huybrechts and de Wolde, 1999; Oerlemans, 2002). Given proxy records of CO_2 of only 1 to 2× PAL since the late Oligocene (Pagani et al., 2005; Beerling and Royer, 2011), these results rule out substantial EAIS retreat due directly to surface mass loss.

East Antarctica has several large sub-glacial basins with beds well below sea level (Wilkes, Aurora, and groups on the eastern side of the Filchner–Ronne ice shelves being the largest; Fig. 1). Although generally not as deep and wide as in West Antarctica, these basins all have grounding lines in contact with the modern ocean at depths of hundreds of meters, and beds deepening upstream to ∼1 km or more below sea level with the potential for marine instabilities. The combined ice volume above flotation in these basins is equivalent to ∼15 to 20 mesl, which could account for the inferred Cenozoic sea level variability.

In most prior 3-D ice-sheet models with some representation of marine physics (Ritz et al., 2001; Huybrechts, 2002; Pollard and DeConto, 2009; Nowicki et al., 2013), WAIS retreats drastically in past and future warm climates, but grounding lines in East Antarctic basins retreat only slightly from modern positions even with substantial ocean warming. Presumably this is because East Antarctic basins have shallower and narrower sills at modern grounding lines, greater buttressing by floating ice in the narrower embayments, and frozen or stiffer beds. However, two recent studies (Fogwill et al., 2014; Mengel and Levermann, 2014) have produced significant retreat in some East Antarctic basins due to oceanic warming with the PISM ice-sheet model, suggesting some model dependency in this behavior. East Antarctic basin retreat is also found in a recent model intercomparison study for the Pliocene, but may be dependent on the imposed initial conditions (de Boer et al., 2014, and interactive discussion). These models use simplified or hybrid treatments of ice dynamics (e.g., Pollard and DeConto, 2012), and it would be desirable to confirm the behavior with higher-order dynamical treatments, but simulations with such models are currently feasible only on smaller scales, and model intercomparisons to date (in which hybrid models have generally performed well) have been confined to idealized geometries (Pattyn et al., 2013).