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Cenozoic variations of the Antarctic Ice Sheet: A model-data mismatch?

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Summary Cenozoic variations of global ice volume deduced from δ18O deep-sea-core records are compared with results from 3-D ice sheet-climate models. After the initial growth of major Antarctic ice at the Eocene-Oligocene boundary ~34 Ma, δ^{18}O records indicate numerous excursions throughout the Oligocene and early Miocene with timescales of ~10^5 to 10^6 years and amplitudes of ~20 to 80 meters of sea level. During most of this period, proxy atmospheric CO_2 levels in proxy records were low, around 1x pre-industrial. These observations conflict with coupled model results that once a large East Antarctic ice sheet formed at 34 Ma, CO_2 levels must have been in the ~3x to 4x range to induce significant retreat and re-growth. Several mechanisms are discussed that could possibly have caused large ice-volume fluctuations, all of which are highly speculative.

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Introduction

Since the first major Cenozoic ice growth on Antarctica around the Eocene-Oligocene boundary (34 Ma), deep-sea core records of benthic foraminiferal δ^{18}O indicate significant ice volume variations through the Oligocene and Miocene. These variations include orbital cycles with δ^{18}O amplitudes of ~0.5 ‰, and distinct events and transitions with timescales of several 10^5 to 10^6 years and amplitudes up to ~1 ‰ (Zachos et al. 2001; Pekar et al. 2006; Pekar and DeConto, 2006; Palike et al., 2007). Benthic δ^{18}O records are affected both by global ice volume and local sea-water temperature, but several lines of evidence suggest that much of the signals are due to ice volume: (i) measurements of foraminiferal Mg/Ca ratios (Lear et al., 2004), (ii) calibrations using independent sequence stratigraphy (Pekar et al., 2006; Pekar and DeConto, 2006), and (iii) inverse ice-sheet modeling (Oerlemans, 2004a,b). This is especially true for distinct events such as Oi2, Mi1, etc. The relationship with ice volume also depends on the isotopic depletion of the ice sheets relative to sea water, but assuming reasonable values of -35 to -50 ‰, Pekar et al.'s analysis implies that the amplitudes of the major events ranged from ~20 to 80 m of eustatic sea level (msl). Sequence stratigraphy alone suggests slightly smaller but still substantial amplitudes of several tens of msl (Van Sickel et al., 2004). The amplitude of the first major event, Oi1 at 34 Ma, is estimated to be particularly large, ~100 to 150 msl (Coxall et al., 2005).

Abundant evidence from Antarctic terrestrial, shelf and offshore environments indicates that Antarctic ice sheets were responsible for Cenozoic ice volume variations before ~5 Ma (Anderson, 1999); there is scant evidence of any Northern Hemispheric ice until the Pliocene (but see Eldrett et al., 2007). On the face of it, this poses two glaciological problems:

1. The first major increase in ice volume at 34 Ma (Oi1 event) considerably exceeds the accomodation space of the Antarctic continent, judging from the modern East Antarctic Ice Sheet (EAIS), currently ~65 msl.
2. Subsequent major events (Oi2, Mi1, etc.) imply substantial retreat and regrowth of the full EAIS, requiring large climate variations to overcome the inherent hysteresis in ice-sheet extent versus climatic forcing.

Here we focus on the second problem, although both may be linked. The nature of the hysteresis is outlined, and modeling efforts at quantifying it for EAIS are described. It is argued that the required climatic variations in surface melt around the Antarctic margins, if due to atmospheric CO_2, are inconsistent with Cenozoic proxy CO_2 records (Pagani et al., 2005; Royer, 2006). Several possible remedies are considered, including thick marine ice on West Antarctica, basal hydrologic cycles, undetected fluctuations in atmospheric CO_2, and Northern Hemispheric ice.

Ice sheet - climate hysteresis

Many modeling studies have shown that ice sheets can respond non-linearly as climate varies, with sudden transitions in ice-sheet size between multiple stable branches (e.g., Weertman, 1961; Oerlemans, 2002). For a flat continent bounded by the ocean, the hysteresis is pronounced (Oerlemans, 2002; his Fig. 1), and stems straightforwardly from consideration of the relative surface areas of ice above and below the equilibrium-line altitude (ELA, the level where annual accumulation balances ablation). Starting with no ice, the climate must cool considerably to lower the ELA to the bedrock surface before any ice appears, which then forms a full continental ice sheet discharging into the ocean. Conversely, starting with a full ice sheet, the climate must become much warmer before melt around the flanks exceeds flow from the interior and retreat is initiated. At that point, the positive feedback of more melt with lowering ice surface (Height-Mass Balance Feedback, HMBF) produces runaway wastage of the entire ice sheet.

Ice-albedo feedback can also produce similar non-linear hysteresis in simple models, despite entirely different physical mechanisms (e.g., North, 1984). It has been investigated for Antarctica using energy-balance and global climate models (EBMs, GCMs) by Crowley et al. (1994), Maqueda et al. (1998) and Ogura and Abe-Ouchi (2001). It is only partly captured in our simulations shown below; however, its effects are similar and have the same sign as HMBF, so it would be expected to augment and increase the hysteresis here.

The idealized HBMF hysteresis described above does not apply exactly to the real EAIS because of the latter's mountain ranges and sloping ELAs, but is a useful first approximation. Two important quantities are:

(i) the width of the hysteresis (separation of the warming and cooling branches) in terms of summer air temperatures T around the flanks, roughly related to ELA by $\partial T/\partial(ELA) \approx .010\ ^{o}\mathrm{C\ m}^{-1}$, and

(ii) the amount that the modern ELA (or summer temperatures) is lower (colder) than that required to initiate ice retreat.

These concepts were first investigated in the context of Cenozoic Antarctica using 3-D ice-sheet models and prescribed climate variations by Oerlemans (1982a) and Huybrechts (1993, 1994). Huybrechts found ice-volume hysteresis in experiments with a cooling climate starting with no ice, versus warming climates starting with full ice; however, the amount of hysteresis was quite small, with only ~1 ^{o}C difference in air temperature separating the growing and receding branches, or ~4 ^{o}C with flat bedrock topography. He also found that the climate range in which the transitions occur is ~10 to 20 ^{o}C warmer than present; i.e., the modern Antarctic climate would have to warm that much to cause appreciable retreat of the EAIS.

Pollard and DeConto (2005, henceforth PD05) performed related experiments with a 3-D Antarctic ice sheet model driven continuously through 10 million years, using look-up tables of stored GCM solutions. Their main results of ice volume versus time are shown in Fig. 1. In these runs a prescribed gradual decline or increase of atmospheric CO_2 causes non-linear transitions in ice volume due to the feedbacks described above. Higher-frequency variability is due to prescribed idealized Milankovitch orbital cycles. The transitions in the cooling vs. warming branches in Fig. 1a occur at CO_2 values of ~2.8x and 3.3x PAL (Pre-industrial Atmospheric Level) respectively, which roughly corresponds to a difference in summer air temperature around Antarctica of ~1 to 2 ^{o}C (see PD05, their Fig. 6). However, this separation (the hysteresis width) is reduced by the orbital "noise" which tends to facilitate transitions, as discussed in PD05. With no orbital forcing, the separation in Fig. 1b is considerably greater, ~2.2x to 3.3x PAL, or ~3 to 5 ^{o}C in summer flank temperatures. These hysteresis widths are of the same order but somewhat larger than those in Huybrechts (1993, 1994), perhaps due to differences in the treatment of precipitation (PD05).

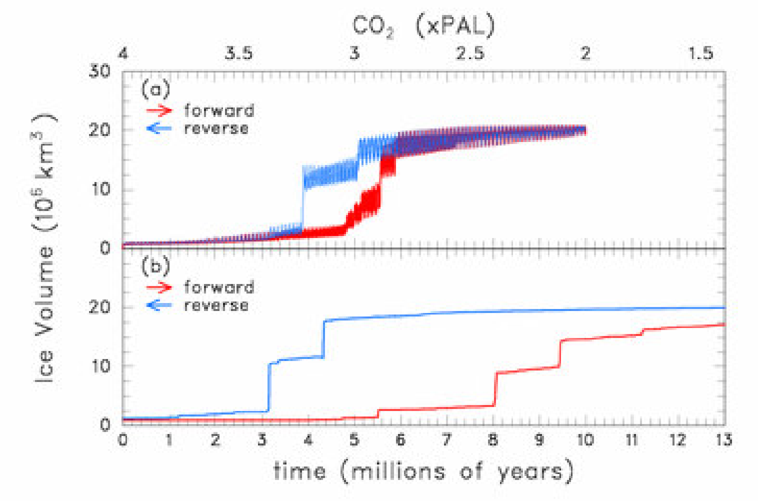

Figure 1. Antarctic ice volumes in ~10 million-year climate-ice sheet simulations (from PD05, copyright Elsevier). **(a)** Red curve runs from left to right with atmospheric CO_2 gradually decreasing. Blue curve runs right to left, with CO_2 increasing. **(b)** As (a) except with no orbital forcing.

The general CO_2 range in which the transitions occur in Fig. 1, around 3x PAL, corresponds to flank temperatures about 10^{o}C warmer than present (PD05, their Fig. 6). However, these paleoclimate simulations do not directly pertain to the future; in additional "snapshot" experiments without orbital forcing and with proper ice-sheet albedo feedback, we find that CO_2 levels need to be elevated to ~6-8x PAL to induce significant retreat of the modern EAIS, which corresponds to ~20 ^{o}C flank warming and is more in line with Huybrechts' upper envelope.

Relation to Cenozoic Antarctic records

The combined results of Huybrechts (1993, 1994) and PD05 are that (i) summer temperatures around Antarctic flanks need to be at least 10 ^{o}C warmer than present to cause appreciable retreat of a full continental EAIS, and ~20 ^{o}C warmer to produce no ice, and (ii) non-linear transitions between no ice, small ice caps and full continental ice cover require summer air temperatures to vary within that range, i.e., ~10 to 20 ^{o}C warmer than present. GCM modeling in PD05 indicates that this requires atmospheric CO_2 to vary between ~3 and 4x PAL when orbital forcing is included. Below that range (~2.5x and below), the only stable state is a full continental ice sheet discharging into the ocean, like the modern EAIS.

Proxy records of atmospheric CO_2 levels through the Cenozoic are uncertain, but recent studies consistently indicate that CO_2 levels fluctuated around 3-4 PAL or above in the Eocene-early Oligocene, but since then have been much more stable, falling below 2x PAL (560 ppmv) in the mid Oligocene and remaining at around 1x PAL (280 ppmv) throughout the Miocene (Pagani et al., 2005; Royer, 2006). The CO_2 records and the modeling described above offer a consistent explanation of the growth of a full EAIS at the Eocene-Oligocene boundary (Oi1, 34 Ma) as a non-linear response to falling CO_2 (DeConto and Pollard, 2003). Since the mid Oligocene, however, according to the modeling above, a full continental EAIS, once formed, would have remained in that state because CO_2 levels have remained far below the levels needed to induce transitions. In that state, as at present, there is little or no surface melting on the EAIS, and its boundaries are constrained only by the ocean. At CO_2 levels below ~2x PAL, only minor volume changes are possible, primarily from expansion and contraction of grounding lines (discussed below).

Essentially the same model-data mismatch was articulated by Huybrechts (1993) regarding the Pliocene, and we merely re-iterate it here in terms of CO_2 levels, for earlier periods, and making use of newer core records and modeling.

Other possible mechanisms

We now outline various mechanisms that could possibly have caused large Cenozoic ice volume variations without high levels of atmospheric CO_2. The first two are also discussed in Huybrechts (1993).

West Antarctic and Continental Shelf Ice. The present marine West Antarctic Ice Sheet (WAIS), grounded predominantly well below sea level, is considered to be much more vulnerable than EAIS to small climatic variations, especially sea level and ocean temperatures (Weertman, 1974; Hughes, 1975; Rignot and Jacobs, 2002). Unfortunately, this suggestion has several drawbacks regarding the Cenozoic: (i) WAIS may not have existing prior to the mid Miocene (Scherer, 1991; De Santis et al., 1999; Anderson, 1999), (ii) its present volume only accounts for ~6 msl, not enough to solve the model-data mismatch described above, and (iii) at the Last Glacial Maximum, when West and East Antarctic grounding lines expanded to the continental shelf break, the total additional Antarctic ice compared to the present was ~15 to 20 msl (Ritz et al., 2001; Huybrechts, 2002), enough to significantly ameliorate the mismatch; however, these Pleistocene WAIS variations have been forced mainly by ~120 m sea level variations due to Northern Hemispheric ice-sheet growth and decay, which were presumably absent in the Oligocene and Miocene. Volume changes due to variations in interior snowfall rates alone in those studies are just a few msl.

Considerably larger Cenozoic ice volume variations could have ensued if the entire WAIS area and its continental shelves were repeatedly overridden by 3 to 4 km thick ice comparable to EAIS, forming a giant single-domed “AIS”. This would require the bed in WAIS regions to have been much stiffer than today, with much less deformable sediment and streaming ice, and probably also would have required shallower regional bathymetry to allow grounding lines to expand. However, this scenario conflicts fundamentally with the established view of WAIS history based on seismic studies of Ross and Weddell Sea sediments, sediment cores in the Victoria Land region, and geophysical tectonic studies, which show no evidence of an early “mega WAIS” or shallower bathymetry (DeSantis et al., 1999; Anderson, 1999; Naish et al., 2001).

Basal Hydrologic Cycles. The recent discoveries of many subglacial lakes beneath East and West Antarctic Ice Sheets, some with interconnected drainages (e.g., Wingham et al., 2006; Bell et al., 2007; Fricker et al., 2007), suggests the possibility of large-scale build up of basal melt water and sudden surges of large parts of the EAIS, similar to the binge-purge cycles proposed for Northern Hemispheric ice sheets (Oerlemans, 1982b; MacAyeal, 1993; Marshal and Clark, 2002). The time and space scales on which these cycles might have occurred under the Cenozoic EAIS are open research questions.

Unresolved Fluctuations in Atmospheric CO_2. Proxy records of atmospheric CO_2 (e.g., Pagani et al., 2005; Royer, 2006) have relatively poor time resolution. It is conceivable that short (~10^5 year) intervals with elevated CO_2 levels of 3 to 4x PAL could have occurred that are undetected by these records, perhaps reflected in a few other more variable records (Retallack, 2002; Royer, 2006). If so, these could have induced drastic retreats of EAIS and explain some of the major Oligocene and Miocene $\delta^{18}O$ events, perhaps involving internal feedbacks between ice volume and the carbon cycle (Zachos and Kump, 2005), and allowing alignments with infrequent orbital nodes (Holbourn et al., 2005; Palike et al., 2006).

Northern Hemispheric Ice Sheets. Although the prevailing view is that significant Northern Hemispheric ice growth only occurred after ~7 to 5 Ma, this is based mainly on the absence of earlier glaciological evidence, and increasing deep-sea-core $\delta^{18}O$ values through the Pliocene (Zachos et al, 2001.). Neither conclusively rules out earlier contributions by large Northern Hemispheric ice sheets; in fact a much earlier inception of ice on Greenland has recently been suggested (Eldrett et al., 2007). In ongoing work with our coupled GCM-ice model, we find that extensive Northern Hemispheric ice sheets can grow during the Oligocene and Miocene if CO_2 falls to ~1x PAL, within the envelope allowed by proxy CO_2 records discussed above. Northern hemispheric ice could even have contributed to the large Oi1 growth at 34 Ma if CO_2 dropped rapidly from ~3 to 1x PAL within a few 10^5 years after the growth of Antarctic ice, addressing the first problem noted in the introduction (DeConto and Pollard, in preparation). If large Northern Hemispheric ice sheets existed in the Oligocene and/or Miocene, they would have been subject to orbital forcing and ~100 and 400 kyr cycles as in the Pleistocene, and could offer a solution to the second problem as well.

Concluding remarks

The model-data mismatch noted by Huybrechts (1993) is still with us, even in the light of more detailed and comprehensive deep-sea core records, CO_2 proxy records, and additional GCM-ice sheet modeling. That is, the relatively low atmospheric CO_2 levels and air temperatures through the late Oligocene and Miocene are insufficient in models to induce significant retreat of the full continental EAIS once it formed at the Eocene-Oligocene boundary. This finding conflicts with numerous ice-volume fluctuations, equivalent to ~20 to 80 msl, indicated by Oligocene and Miocene $\delta^{18}O$ deep-sea core records. Several mechanisms that could possibly have produced ice volume variations of this magnitude are discussed above, all of which are speculative at best, but are testable with further modeling and data acquisition.

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