The Mid-Brunhes Event and West Antarctic Ice Sheet stability

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Abstract

The complex cyclical nature of Pleistocene climate, driven by the evolving orbital configuration of the Earth, is well known but not well understood. A major climatic transition took place at the Mid-Brunhes Event (MBE), ~430 ka BP after which the amplitude of the ~100 ka climate oscillations increased, with substantially warmer interglacials, including periods warmer than the present. Recent modelling has indicated that whilst the timing of these Warmer-than-Present-Transient (WPT) events is consistent with southern warming due to a deglaciation-forced slowdown of Atlantic Meridional Overturning Circulation, the magnitude of warming requires a local amplification, for which a candidate is the feedback of significant West Antarctic Ice Sheet (WAIS) retreat. We here extend this argument, based on the absence of WPTs in the early ice-core record (450 to 800 ka BP), to hypothesise that the MBE could be a manifestation of decreased WAIS stability, triggered by ongoing subglacial erosion.

Introduction

Radiative forcing due to changing orbital conditions, greenhouse-gas concentrations and Northern Hemisphere ice sheets is sufficient to reproduce the general evolution of Antarctic temperature over the last 800,000 years, but does not appear sufficient to explain the warmer-than-present Antarctic climates observed during recent interglacials (Masson-Delmotte et al 2010a; Holden et al 2010). Observational data suggests that the bipolar seesaw (Stocker and Johnsen 2003), triggered by Northern Hemisphere deglaciation, may be implicated in these transient Antarctic warming events (Cheng et al 2009; Masson-Delmotte et al 2010a; Masson-Delmotte et al 2010b). Climate model simulations (Ganopolski and Roche 2009; Masson-Delmotte et al 2010a; Holden et al 2010) support this hypothesis although these studies were not able to reproduce the observed magnitude of WPTs from consideration of the bipolar seesaw alone. Holden et al (2010) demonstrated that if significant WAIS retreat were associated with WPTs, this could have provided a sufficient feedback to match the magnitude of the warming. Given that climate evidence supports the possibility of WAIS retreat during WPTs, we argue that the lack of warmer-than-present interglacials in the earlier ice core record may reflect a more stable ice sheet so that, by inference, the MBE may be the consequence of crossing a WAIS stability threshold. Although this hypothesis is derived largely from indirect evidence it is consistent with observations and modelling of climate, ice-sheet dynamics and sub-glacial bedrock erosion.

Simulations of East Antarctic temperature over eight glacial cycles

Figure 1a plots the East Antarctic temperature reconstructions derived from DOME C δD (Jouzel et al 2007). During the last 800,000 years, the only interglacials that exhibit Antarctic temperatures significantly greater than the Holocene are MIS 5.5, 7.5, 9.3 and 11.3. In addition to the Holocene, early interglacial optima are apparent during MIS 5.5, 7.5 and 9.3 (WPTs) and MIS 19.3.

Figure 1b plots the annually-averaged East Antarctic temperature anomaly from a transient 800,000 year GENIE-1 simulation. This simulation, previously described in detail in Holden et al (2010), was forced with the orbital parameters of Berger (1978), prescribed atmospheric CO_2 (Lüthi et al 2008) and prescribed transient ice sheets, together with associated meltwater fluxes. The changing Laurentide and Eurasian ice sheets were defined by interpolating the spatial distribution of Ice-4G (Peltier 1994) onto the benthic $\delta^{18}O$ record (Lisiecki and Raymo 2005). Greenland and Antarctic ice sheets were held fixed at their modern topography.

The simulated East Antarctic temperature anomaly exhibits a correlation of R=0.87 with respect to the ice core reconstruction, reflecting the correlation between the δD record and the prescribed radiative forcing due to changing CO_2 (0.89) and ice sheet volume (0.86). Modelled cooling at glacial maxima is consistent with observations and generally greater post-MBE. Interglacials prior to the MBE are generally 1 to 1.5°C cooler than pre-industrial, again in agreement with observations, although the full magnitude of the MIS 19 early optimum warming is not simulated. In contrast, the simulated warming during the four warm post-MBE interglacials is consistently ~4°C lower than the observed maxima. The model cannot create interglacials substantially warmer than the Holocene. A detailed discussion of the uncertainties associated with an analysis of this type can be found in Masson-Delmotte et al (2010a) who concluded that the mismatch may result from the lack of feedbacks between ice sheets and climate, including both local effects due to changes in ice sheet topography and global effects due to meltwater–thermohaline circulation interplays. The failure of GENIE-1 during recent interglacials is demonstrated in Fig 1c, which plots the difference between the δD reconstruction and the simulation.

Figure 1d illustrates the East Antarctic temperature anomaly from three simulations that vary the forcing due to each of orbit, CO_2 and ice-sheets in isolation, with fixed forcings held at their initial (glacial) conditions. Orbital forcing produces a 2σ variability of ±1.8ºC in the simulated East Antarctic temperature. The timing of the simulated variability suggests that local insolation is unlikely to provide an explanation for early interglacial warmth as the δD optima are all associated with orbitally-forced temperature minima, although some caution should be exercised in view of the simple atmospheric model in GENIE-1 which does not allow a robust treatment of possible changing seasonality of precipitation. Possible biasing of the δD record due to changed seasonality of precipitation has been demonstrated in HadCM3 simulations of warm interglacials forced by elevated CO_2 (increased winter precipitation, Sime et al 2009) or by WAIS retreat (increased summer precipitation, Holden et al 2010).

Figure 1e plots the East Antarctic temperature anomaly due to deglacial meltwater forcing. This analysis, together with an ensemble of transient GENIE-1 simulations and snapshot simulations with HadCM3 (Holden et al 2010), demonstrated that a meltwater-induced bipolar seesaw is likely insufficient to explain the magnitude of warmth. We note that idealised CLIMBER-2 simulations across a glacial termination demonstrated the magnitude of warming was sensitive to the rate of meltwater discharge, suggesting that qualitative differences between terminations may be driven by differences in deglaciation rates (Ganopolski and Roche 2010). In contrast to the recent record, simulated meltwater anomalies prior to the MBE are never associated with Antarctic climates warmer than present. MIS 19.3 is especially interesting as this interglacial shows a strong similarity with late Holocene levels of methane and CO_2 (Pol et al 2010), but exhibited an early optimum that apparently did not exceed late Holocene temperatures.

West Antarctic Ice Sheet Stability

Snapshot simulations with HadCM3 demonstrated that the magnitude of post-MBE interglacial warming is reproduced under the assumption of significant WAIS retreat with precipitation-weighted East Antarctic temperatures ~5ºC above pre-industrial (Holden et al 2010). This warming signal arises from the combined effects of reduced West Antarctic albedo and seasonal biasing by increased East Antarctic summer precipitation. The climate simulations are therefore consistent with the possibility that repeated WAIS retreat occurred in recent interglacials. We here suggest the possibility that the MBE may have been a manifestation of decreased WAIS stability.

Although the WAIS is believed to be potentially unstable (Oppenheimer 1998), direct evidence for possible WAIS retreat is limited because ice-sheet advances have obliterated much of the proximal marine record, whilst the record further offshore may be ambiguous (Barnes and Hillenbrand 2010). The direct evidence that does exist suggests that the WAIS apparently retreated at least once during the Pleistocene (Scherer et al 1998; Barnes and Hillenbrand 2010). Hillenbrand et al (2009) identified a period of anomalous sedimentation spanning MIS15 to MIS 13 that hints at the possibility of significant WAIS retreat. A major retreat of WAIS during this period might prove difficult to reconcile with our hypothesis as there is no apparent temperature anomaly to explain at this time. Indirect evidence of possible retreat during recent interglacials is provided from estimates of sea-level high stands (Siddall et al 2006) at MIS 5: 0 to 6 m, MIS 9: -3 to 8 m and MIS 11: -3 to 18 m. More recent analysis of a range of sea-level indicators indicated that global sea levels peaked at least 6.6 m higher (95% confidence) than present during the last interglacial (Kopp et al 2009). At least the upper limits of these ranges are difficult, if not impossible, to explain without a contribution from Antarctica as even the total melting of the Greenland Ice Sheet would only raise sea level by 7 m (Letréguilly et al 1991).

An ice-sheet simulation over the last 405,000 years simulated WAIS retreat equivalent to ~1.4 m sea-level rise during MIS 5 as the result of grounding line retreat triggered by sea-level rise during the termination (Huybrechts 2002). Substantial uncertainties in the magnitude of retreat were identified, in particular with respect to climatic forcing and to the treatment of isostatic rebound. More recently it has been proposed that marine-based ice sheets may have a discrete set of steady surface profiles whose stability is dependent upon the bedrock gradient (Schoof 2007). The outflow rate at the grounding line increases with bedrock depth, so that if the bedrock slopes downward inland, as is the case for the WAIS (Lythe et al 2000) a point of instability may exist, beyond which further retreat results in ice loss through the grounding line exceeding net accumulation, accelerating the retreat. A recent ice-sheet simulation (Pollard and DeConto 2009) which incorporated this instability through a parameterisation of grounding-line dynamics, produced multiple WAIS retreats during the Pliocene in addition to several major Pleistocene retreats, with transitions into and out of interglacials taking place over one to several thousand years. The timing of simulated retreats was subject to substantial forcing uncertainties but demonstrated the potential for substantial WAIS retreat at terminations as required by our hypothesis.

A possible explanation for progressively decreasing WAIS stability relates to ongoing erosion. The modern WAIS bedrock profile is primarily a consequence of subglacial erosion (Anderson 1999). Ice streams are today responsible for more than 90% of the discharge of Antarctic ice and are potentially key to WAIS stability (Bennett 2003). Erosion rates in the Whillans Ice Stream vary from 0.2 to 2 mm a^{-1} (Engelhardt and Kamb 1998, Alley et al 1989). Seismic surveys of bed topography under the Rutford Ice Stream revealed erosion rates as high as 1 m a^{-1} across a narrow (~500m) section over a six year period (Smith et al 2007). Although poorly constrained, modelling of erosion beneath Ice Stream C derived average erosion rates of ~0.6 mm a^{-1} in tributaries and ~0.2 mm a^{-1} in the trunk (Bougamont and Tulaczyk 2003). These rates could have generated the relief of Ice Stream C within ~10^6 years, potentially associated with a substantial increase in bedrock gradient, the progressive outward advance of the point of instability and reduced WAIS stability.

Conclusions

In summary, several lines of both observational and modelling evidence indicate that the warmth during the early stages of the last three interglacials was driven by the bipolar seesaw during terminations. Recent modelling suggested that a feedback associated with significant WAIS retreat would supply the observed magnitude of Antarctic warming. However, prior to the MBE, Antarctic interglacial temperatures are readily simulated under the assumption of the modern Antarctic ice sheet configuration, requiring no additional amplification, such as that supplied by substantial WAIS retreat. These arguments suggest the possibility that the MBE may have been a manifestation of decreasing WAIS stability, consistent with ongoing erosion of the submarine bedrock. We note that the location of potential points of WAIS instability are climate dependent, with increased accumulation, decreased ice temperature or lower sea-levels acting to stabilize the ice sheet (Schoof 2007), so that this inference does not conflict with the obliquity-paced WAIS retreats that were inferred during the warmer climate of the Pliocene (Naish et al 2009). We note that relative strength of the obliquity component of the DOME C δD power spectra has been increasing over the last 800,000 years (Jouzel et al 2007). The inferred initial retreat during MIS 11, not associated with the termination but occurring in the middle of the long interglacial, and apparently consistent with an observed strengthening of Atlantic overturning at 415 kyr BP (Dickson et al 2009), would presumably have been accompanied by further erosion, reducing topographic buttressing and leading to further destabilisation.

Two recent studies suggest possible ways to test this hypothesis. Firstly, an ice-sheet model incorporating the necessary parameterisation of grounding-line dynamics (Pollard and DeConto 2009) coupled to an Earth System Model of appropriate complexity, would enable an investigation of coupled ice-sheet/ocean/climate feedbacks and the role of changing bedrock gradients on WAIS stability. Secondly, spatial variation of the Antarctic isotopic signature during warm interglacials has been demonstrated, suggesting the possibility that existing δD reconstructions may in fact underestimate the magnitude of warm interglacials (Sime et al 2009). An extension of this analysis could be used to test the impacts of bipolar warming and WAIS retreat on the isotopic record and provide an improved evaluation of the consistency of the hypothesis with Antarctic ice core records. However, new observational constraints on the size of WAIS during recent interglacials could provide more direct evidence needed to support or reject these ideas.

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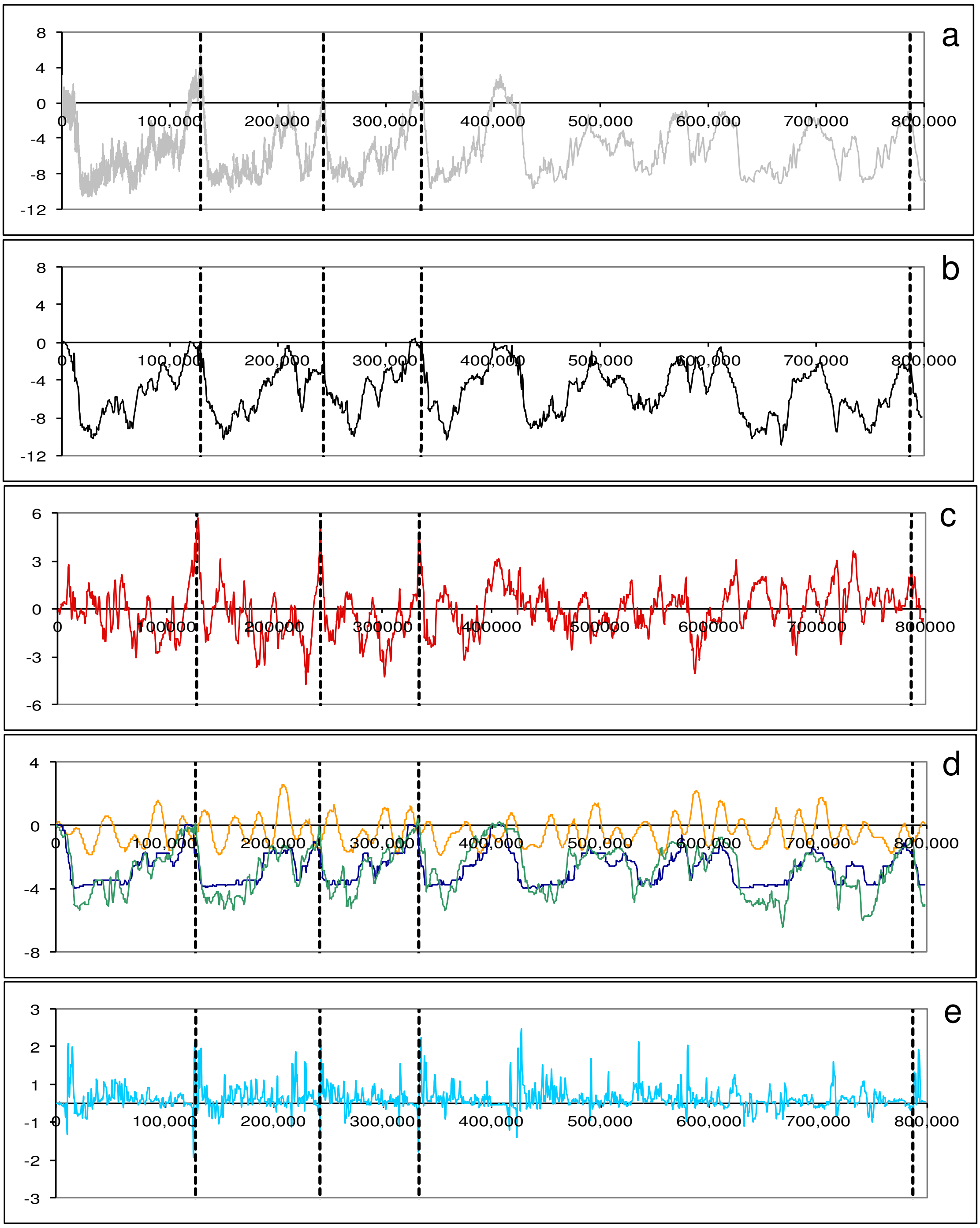
Figure 1

(a) δD-inferred temperature anomaly from DOME C (Jouzel et al 2007). (b) GENIE-1 temperature anomaly with respect to pre-industrial (sea-level equivalent, annually averaged across East Antarctica, south of 71°S), from the simulation described in Holden et al (2010). Boundary conditions (orbital forcing, prescribed atmospheric CO_2, transient ice sheets and associated meltwater fluxes) are described in the text. (c) The difference between observations and simulations (a-b) highlighting the absence of interglacial warmth in the simulated post-MBE temperature optima that are the focus of this work. (d) GENIE-1 temperature anomaly with respect to pre-industrial (sea-level equivalent, annually averaged across East Antarctica, south of 71°S) when orbital (orange), Laurentide and Eurasian ice sheet (blue) and CO_2 (green) forcing are applied in isolation. The dominant feedbacks in this configuration of GENIE arise from dynamical changes in ocean circulation, vegetation, sea ice and snow cover. (e) The meltwater-induced Antarctic temperature anomaly (the difference between simulations that include and neglect meltwater forcing). The early interglacial optima during MIS 5.5, 7.5, 9.3 and 19.3 are illustrated with vertical dashed lines.



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