Palaeogeography, Palaeoclimatology, Palaeoecology 309 (2011) 98–110

Contents lists available at ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

journal homepage: www.elsevier.com/locate/palaeo

Sensitivity of Pliocene ice sheets to orbital forcing

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ARTICLE INFO

Article history:
Received 31 October 2010
Received in revised form 11 March 2011
Accepted 26 March 2011
Available online 1 April 2011

Keywords:
Pliocene
Ice sheets
Orbital forcing
Sea level

ABSTRACT

The stability of the Earth's major ice sheets is a critical uncertainty in predictions of future climate and sea level change. One method of investigating the behaviour of the Greenland and the Antarctic ice sheets in a warmer-than-modern climate is to look back at past warm periods of Earth history, for example the Pliocene. This paper presents climate and ice sheet modelling results for the mid-Pliocene warm period (mPWP; 3.3 to 3.0 million years ago), which has been identified as a key interval for understanding warmer-than-modern climates (Jansen et al., 2007). Using boundary conditions supplied by the United States Geological Survey PRISM Group (Pliocene Research, Interpretation and Synoptic Mapping), the Hadley Centre coupled ocean–atmosphere climate model (HadCM3) and the British Antarctic Survey Ice Sheet Model (BASISM), we show large reductions in the Greenland and East Antarctic Ice Sheets (GrIS and EAIS) compared to modern in standard mPWP experiments. We also present the first results illustrating the variability of the ice sheets due to realistic orbital forcing during the mid-Pliocene. While GrIS volumes are lower than modern under even the most extreme (cold) mid-Pliocene orbit (losing at least 35% of its ice mass), the EAIS can both grow and shrink, losing up to 20% or gaining up to 10% of its present-day volume. The changes in ice sheet volume incurred by altering orbital forcing alone means that global sea level can vary by more than 25 m during the mid-Pliocene. However, we have also shown that the response of the ice sheets to mPWP orbital hemispheric forcing can be in anti-phase, whereby the greatest reductions in EAIS volume are concurrent with the smallest reductions of the GrIS. If this anti-phase relationship is in operation throughout the mPWP, then the total eustatic sea level response would be dampened compared to the ice sheet fluctuations that are theoretically possible. This suggests that maximum eustatic sea level rise does not correspond to orbital maxima, but occurs at times where the anti-phasing of Northern and Southern Hemisphere ice sheet retreat is minimised.

1. Introduction

1.1. Significance of the Pliocene

There is significant uncertainty in the response of the cryosphere to future climate change (Lemke et al., 2007) and therefore there is increasing interest in understanding the nature and behaviour of the major ice sheets during warm intervals in Earth history. One Epoch of geological time receiving considerable attention is the Pliocene, specifically warm 'interglacial' events within the Pliocene. The mid-Pliocene Warm Period (mPWP) lasting from 3.26 to 3.025 Ma (Dowsett et al., 2010) is a particularly well documented interval of warmth during the Pliocene. Global data sets of multi-proxy sea surface temperatures, vegetation cover, topography and ice sheet extent are readily available as boundary conditions for global climate models (Haywood et al., 2002; Dowsett et al., 2010; Haywood et al., 2010). The most recent climate model predictions (e.g. Haywood et al., 2009; Lunt et al., 2010) suggest that during the mPWP global annual mean temperatures were 2 to 3 °C higher than the pre-industrial era and the most recent and detailed estimates of mPWP carbon dioxide concentrations in the atmosphere (e.g. Pagani et al., 2010; Seki et al., 2010) range between 330 and 450 ppmv.

Sea levels were higher than today (estimated to be 5 to 40 m) meaning that global ice volume was reduced (Dowsett and Cronin, 1990). There may have been large fluctuations in ice cover on Greenland and West Antarctica, and during the interglacials they may have been largely free of ice (Lunt et al., 2008b, 2009; Naish et al., 2009; Pollard and DeConto, 2009). Some ice may also have been lost

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0031-0182/$ – see front matter
doi:10.1016/j.palaeo.2011.03.030

from around the margins of East Antarctica especially in regions such as the Aurora and Wilkes sub-glacial basins (Hill et al., 2007; Williams et al., 2010). Coniferous forests replaced tundra in the high latitudes of the Northern Hemisphere, and the Arctic Ocean may have been seasonally free of sea-ice (Cronin et al., 1993; Moran et al., 2006; Robinson, 2009; Polyak et al., 2010).

1.2. Numerical model predictions of Pliocene ice sheets

In an attempt to improve our understanding of the cryosphere during the Pliocene, and in turn, to increase our understanding of bi-polar ice sheet stability in a warmer-than-modern world, a number of modelling studies have been undertaken (Huybrechts, 1993; Hill et al., 2007; Lunt et al., 2008b; Hill, 2009; Lunt et al., 2009; Pollard and DeConto, 2009). Early ice sheet modelling studies simply perturbed modern temperature observations by a given amount (up to 20 °C) to investigate the sensitivity the Pliocene East Antarctic Ice Sheet (EAIS) to past increases in temperature (Huybrechts, 1993). However, advances in palaeoclimate modelling have enabled much more realistic climatologies to be used in models of past climates (such as the Eocene–Oligocene boundary, Pollard and DeConto (2005)). Pliocene climatologies derived from different versions of the United Kingdom Met Office (UKMO) Unified Model (UM) have been used in combination with the UK Community Ice Sheet Model (GLIMMER) and the British Antarctic Survey ice sheet model (BASISM) to characterise equilibrium-state East Antarctic and Greenland Ice Sheets during the mPWP (e.g. Hill et al., 2007; Lunt et al., 2008b; Hill, 2009; Lunt et al., 2009; Hill et al., 2010). Simulated mPWP Antarctic climates were shown to be warmer than modern (with temperatures above freezing during the Antarctic summer (Hill et al., 2007)) and modelled ice sheet reconstructions show ice loss equivalent to around 15 m of sea level rise (Hill, 2009). Modelled mPWP Greenland climates were also warmer than modern and ice sheet volume reductions of up to 80% have been simulated (Lunt et al., 2009; Hill et al., 2010).

In a study investigating the possible causes of increased glaciation in the late Pliocene, Lunt et al. (2008b) showed that using orbital forcing representative of Glacial Inception (115 kyr) and the Last Interglacial (126 kyr) had a significant impact on the amount of ice volume on Greenland, demonstrating the potential for the specific configuration of the orbit to influence mPWP ice sheet volume and extent. To date no other published study has examined the influence of realistic Pliocene orbital forcing on the coupled atmosphere, ocean and ice sheet systems.

Here we investigate the sensitivity of the GrIS and EAIS to orbital forcing specific to the mPWP. We present a suite of new climate model simulations driven by appropriate Pliocene boundary conditions and calculated orbital solutions to: (a) examine the effect on climate and ice sheets of the standard procedure of specifying a modern orbit within model simulations of the mPWP (Haywood et al., 2010), and (b) investigate the behaviour of the GrIS and EAIS under maximum and minimum hemispheric orbital forcing in order to better constrain ice sheet behaviour in a warmer world.

2. Methodology

2.1. Model descriptions

2.1.1. The Hadley Centre coupled climate model version 3

The Hadley Centre coupled climate model version 3 (hereafter referred to as HadCM3) was used throughout this study. Coupled ocean–atmosphere models such as HadCM3, are valuable tools for understanding and predicting climate change (Gordon et al., 2000; Lambert and Boer, 2001) and have also proved useful in modelling past climates (Lü et al., 2001; Haywood and Valdes, 2004; Haywood et al., 2007; Lunt et al., 2008a,b, 2009). A full description of HadCM3 can be found in Gordon et al. (2000) however, some discussion of the model itself is necessary. HadCM3 consists of a coupled atmospheric model, oceanic model and sea-ice model. The horizontal resolution of the atmosphere model is 2.5° in latitude by 3.75° in longitude and consists of 19 layers in the vertical. The atmospheric model has a time step of 30 min and includes a radiation scheme that can represent the effects of major and minor trace gases (Edwards and Slingo, 1996). A parameterisation of simple background aerosol climatology is also included (Cusack et al., 1998). The convection scheme is that of Gregory et al. (1997). A land-surface scheme includes the representation of the freezing and melting of soil moisture. The representation of evaporation includes the dependence of stomatal resistance on temperature, vapour pressure and CO_2 concentration (Cox et al., 1999).

The spatial resolution over the ocean in HadCM3 is 1.25° by 1.25° and the model has 20 vertical layers. The horizontal resolution allows the use of a smaller coefficient of horizontal momentum viscosity leading to an improved simulation of ocean velocities. The ocean model includes the use of the Gent–McWilliams mixing scheme (Gent and Mcwilliams, 1990). There is no explicit horizontal tracer diffusion in the model. The sea-ice model uses a simple thermodynamic scheme and contains parameterisations of ice drift and leads (Cattle and Crossley, 1995).

Gordon et al. (2000) illustrated that HadCM3 is capable of reproducing many aspects of the observed heat budget of the Earth and it has been shown to represent the broad-scale features of the Antarctic and Arctic atmospheric and oceanic circulation well (Turner et al., 2006; Chapman and Walsh, 2007; Zhu and Wang, 2008). Additionally the fact that it consistently performs well in tests against other coupled atmosphere–ocean models (Lambert and Boer, 2001; Hegerl et al., 2007) increases our confidence in HadCM3 palaeoclimate simulations.

2.1.2. The British Antarctic Survey Ice Sheet Model (BASISM)

In this study we used the British Antarctic Survey Ice Sheet Model (BASISM), which has previously been applied to study Pliocene ice sheets (Hill et al., 2007; Hill, 2009; Hill et al., 2010). BASISM is a finite-difference, thermomechanical, shallow ice approximation ice sheet model, utilising an unconditionally stable, implicit numerical solution of the non-linear simultaneous equations of ice flow. The diffusivity is evaluated at grid centres staggered in both x and y directions,

Table 1
Orbital sensitivity experiment details and the astronomical solutions of eccentricity, precession, obliquity and global annual insolation according to Laskar et al. (2004).

Experiment name	Boundary conditions	CO_2 (ppmv)	Orbit	Eccentricity	Precession	Obliquity	Global mean annual insolation ($W\,m^{-2}$)
$PreInd^{Ctrl}$	Modem	280	Modem	0.016702	0.016280	23.4393	342.0477
$Plio^{Mod}$	PRISM2	400	Modem	0.016702	0.016280	23.4393	342.0477
$Plio^{Mean}$	PRISM2	400	3092 k	0.032601	0.023440	22.9322	342.1819
$Plio^{NHmax}$	PRISM2	400	3037 k	0.051086	−0.042388	24.3706	342.4472
$Plio^{NHmin}$	PRISM2	400	3049 k	0.054523	0.052037	23.1432	342.5095
$Plio^{SHmax}$	PRISM2	400	3049	0.054523	0.052037	23.1432	342.5095
$Plio^{SHMin}$	PRISM2	400	3059	0.052947	−0.045328	23.6301	342.4804