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Pliocene Ice Sheet Modelling Intercomparison Project (PLISMIP) – experimental design

A. M. Dolan[1], S. J. Koenig[2], D. J. Hill[3], A. M. Haywood[1], and R. M. DeConto[2]

[1]School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK
[2]Department of Geosciences, University of Massachusetts, Amherst, MA 01003, USA
[3]British Geological Survey, Keyworth, Nottingham, NG12 5GG, UK

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Correspondence to: A. M. Dolan (eeamd@leeds.ac.uk)

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Abstract

During the mid-Pliocene Warm Period (3.264 to 3.025 million yr ago), global mean temperature was similar to that predicted for the next century and atmospheric carbon dioxide concentrations were slightly higher. Sea level was also higher than today, implying a reduction in the extent of the ice sheets. Thus, the mid-Pliocene Warm Period provides a unique testing ground to investigate the stability of the Earth's ice sheets and their contribution to sea level in a warmer-than-modern world. Climate models and ice sheet models can be used to enhance our understanding of ice sheet stability, however, uncertainties associated with different ice-sheet modelling frameworks/approaches mean that a rigorous comparison of numerical ice sheet model simulations for the Pliocene is essential. As an extension to the Pliocene Model Intercomparison Project (PlioMIP; Haywood et al., 2010, 2011a), the Pliocene Ice Sheet Modelling Intercomparison Project (PLISMIP) will address these uncertainties. Here we outline the PLISMIP experimental design and initialisation conditions that have been adopted to simulate the Greenland and Antarctic ice sheets under present day and warm mid-Pliocene conditions. Not only will this project provide a new benchmark in the simulation of ice sheets in a past warm period, but the analysis of model sensitivity to various uncertainties could directly inform future predictions of ice sheet and sea level change.

1 Rationale

The response of the Greenland and Antarctic ice sheets to a warming climate is a critical uncertainty in future predictions of climate and sea level (Lemke et al., 2007; Meehl et al., 2007). The climatic feedbacks associated with changes in the cryosphere are generally not included in climate simulations to 2100 AD. On this timescale the losses in Greenland and Antarctic ice sheets are likely to be small (Huybrechts et al., 2002, 2004; van den Broeke, 2009), but changes will certainly have an impact on long-term

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climate change and scenarios for climate stabilisation (Irvine et al., 2009; Rignot et al., 2011). Current ice sheet models suggest that significant future ice sheet retreat in Greenland and West Antarctica will occur on centennial timescales (Huybrechts and de Wolde, 1999; Greve et al., 2011). However, current models fail to capture the rapid changes that are being observed in the ice sheet today, suggesting more rapid retreat could be possible. Therefore, it is increasingly important to understand the nature and behaviour of the Earth's major ice sheets during warm intervals in Earth history.

The General Circulation Models (GCM) and ice sheet models (ISM) used for simulating future climate change can be applied to retrodict past climatic and ice sheet changes. Unlike future predictions, palaeoclimate and ice sheet simulations can be evaluated against proxy records providing an important test of the model's ability to simulate climates and ice sheets under conditions of enhanced greenhouse gases.

One Epoch of geological time receiving considerable attention is the Pliocene (Haywood et al., 2011b). A number of studies have taken a modelling approach to investigate Pliocene ice sheets (see Sect. 1.1). However, each of these studies involves a single GCM and ISM; and has employed different modelling techniques, strategies and parameterisations. This means that the model dependency of the results remains unquantified. In response to this, the Pliocene Ice Sheet Modelling Intercomparison Project (PLISMIP) was initiated to test and compare the performance of a range of existing numerical ice sheet models of varying complexity when simulating ice sheets of the Pliocene.

1.1 The mid-Pliocene Warm Period

As the most recent period in Earth history with global temperatures and levels of atmospheric carbon dioxide (CO_2) greater than today, the mid-Pliocene Warm Period (mPWP) provides an important target for palaeoclimate and ice sheet modelling. Mid-Pliocene palaeogeography is close to modern, making it suitable for testing Earth System sensitivity and providing an excellent natural laboratory to test climate and ice sheet dynamics in a warmer world. The mPWP is defined by the United States

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Geological Survey's PRISM Group (Pliocene Research Interpretation and Synoptic Mapping[1]) as the interval between isotope stages M2/M1 (3.264 Ma) and G21/G20 (3.025 Ma), according to the geomagnetic polarity timescale of Lisiecki and Raymo (2005). The mPWP "Time Slab" is a climatically distinct period, easily identifiable in marine core records, where the Earth experienced global mean temperatures higher than today. It represents one of the most accessible palaeoclimates to compare with model estimates of late 21st century climate (Haywood et al., 2011b). Additionally, due to the efforts of the PRISM Group, the mPWP is particularly well documented in terms of palaeoenvironmental conditions. Global data sets of multi-proxy sea surface temperatures, vegetation cover, topography and ice volume readily available as boundary conditions for global climate models (see Dowsett et al., 2010 and references therein).

The most recent climate model predictions suggest that during Pliocene interglacials, global annual mean temperatures were 2 to 3 °C higher than the pre-industrial era (e.g. Haywood et al., 2009; Lunt et al., 2010). Sea levels were higher than today (estimated to be 10 to 30+ m) meaning that global ice volume was reduced (Dowsett et al., 2010 and references therein; Raymo et al., 2011). Proxy evidence suggests that there may have been large fluctuations in ice cover on West Antarctica (Naish et al., 2009) and during the interglacials the Greenland ice sheet may have been largely free of ice (Funder et al., 2001; Alley et al., 2010). Some ice may also have been lost from around the margins of East Antarctica (Williams et al., 2010). Unfortunately, much of the geological evidence for this time period is limited and disputed or controversial (see Hill et al., 2007).

Given these uncertainties in geological estimates of Pliocene ice sheets considerable effort has been devoted to accurately simulating the ice sheets with numerical models (e.g. Hill et al., 2007, 2010; Lunt et al., 2008, 2009; Hill, 2009; Pollard and DeConto, 2009; Dolan et al., 2011; Koenig et al., 2011). However, the exact location and extent of the ice sheets remain uncertain as the different modelling frameworks adopted have yielded different results. Through the comparison of a range of ice sheet

[1] http://geology.er.usgs.gov/eespteam/prism/

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models under the same boundary conditions and climatological forcing, PLISMIP will reconstruct the most likely geometry and volume of ice masses on Greenland and Antarctica. In doing so, PLISMIP will also address the issue of ISM dependency.

1.2 PLISMIP within PlioMIP and PMIP

The Palaeoclimate Modelling Intercomparison Project (PMIP) encourages the systematic study of climate models and their predictions (e.g. Joussaume and Taylor, 1995; Hoar et al., 2004; Zheng et al., 2008). GCMs are widely used to simulate and predict the Earth's past, present and future climates (e.g. Solomon et al., 2007). Although broad agreement exists amongst such models, there are significant differences in the details of their predictions, and their sensitivity to increases in atmospheric CO_2. This has necessitated the investigation of model dependencies. Therefore the modelling community has developed initiatives such as PMIP to accurately reconstruct past climates and test models against proxy records. One of the most recent additions to PMIP has been the Pliocene Model Intercomparison Project (hereafter referred to as PlioMIP; Haywood et al., 2010, 2011a), which focuses on comparing climate model simulations of the mPWP.

PlioMIP's two-phase approach includes the application of atmosphere-only and coupled ocean-atmosphere GCMs (Haywood et al., 2010, 2011a). CO_2 levels for the PlioMIP experiments were set to 405 ppmv for the PlioMIP experiments (Haywood et al., 2010, 2011a). PlioMIP boundary conditions are based on the PRISM3 global reconstruction (Dowsett et al., 2010), which incorporates the following:

– A fractional land/sea mask in keeping with an increase of 25 m of sea level relative to modern, which is consistent with palaeoshoreline and marine sedimentary evidence (Dowsett and Cronin, 1990; Wardlaw and Quinn, 1991; Krantz, 1991; Lisiecki and Raymo, 2005; Dwyer and Chandler, 2009; Naish and Wilson, 2009).

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- A basic topographic reconstruction based on the Pliocene palaeogeography of Markwick (2007) where the main area of change from modern is in the ice sheet regions (Sohl et al., 2009).
- Reconstructions of ice sheet height and extent produced with the high-resolution British Antarctic Survey Ice Sheet Model, utilising the Hadley Centre GCM climatologies produced with PRISM2 boundary conditions (Hill et al., 2007; Hill, 2009).
- A sea-surface temperature (SST) field, reconstructed using a warm-peak averaging technique incorporating multiple temperature proxies from multivariate analysis of fossil planktonic foraminifers, ostracods and diatoms as well as Mg/Ca and alkenone unsaturation index palaeothermometry (Dowsett, 2007; Robinson et al., 2008; Dowsett and Robinson, 2009; Dowsett et al., 2009a,b; Robinson, 2009).
- A sea ice reconstruction showing ice-free summers in both hemispheres with a mid-Pliocene maximum winter margin at the modern summer sea ice extent. This reconstruction is consistent with the distribution of key diatom taxa (in the Southern Hemisphere; Barron, 1996) and sedimentological data suggesting that Pliocene high latitude winter SSTs resembles modern summer conditions (Dowsett et al., 1994, 2009a; Robinson, 2009).
- Reconstructed vegetation based on a combination of internally consistent palaeobotanical data from 202 sites and the predictions of a coupled climate-vegetation model (Salzmann et al., 2008).

Eventually PLISMIP will use all of the data resulting from the PlioMIP experiments to help quantify the uncertainties introduced into mPWP ice sheet simulations when using a single GCM. However, it is first necessary to understand the inherent differences that caused by structural uncertainty in ice sheet models. The experimental design for the first stage of PLISMIP focussing on ice sheet model dependency is detailed below. This detailed description of the project design and the rationale behind the data sets used, will prove invaluable during the intercomparison phase of PLISMIP.

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2 Experimental design

The PLISMIP experimental design is divided into three domains based on the predictive capabilities of the two types of ice sheet models. We use models that only apply the shallow-ice approximation (SIA) on land or a combination of the SIA and shallow-shelf approximation (SSA) to include floating ice flow (Pollard 2010; see Sect. 3 for further details). ISMs that use a SIA to represent ice flow will be applied to simulate (i) the East Antarctic Ice Sheet (EAIS) and (ii) the Greenland Ice Sheet (GrIS), while models which use a SSA to represent ice dynamics (see Bueler and Brown, 2009), and therefore have the capability to model the floating marine section of West Antarctica, will be used to model (iii) the whole of Antarctica. A summary of the experimental design is shown in Table 1. For each of the three ice sheet domains five experiments were undertaken (Sect. 2.1).

2.1 Experiments

2.1.1 Control simulations

Control simulations are initiated to understand how well ISMs of differing complexity are able to simulate pre-industrial and modern-day ice sheets, in order to highlight any potential biases in the palaeo simulations.

First, all ISMs are forced with a modern-day climate based on the NCEP reanalysis data set (Kanamitsu et al., 2002), which is partially based on observations (see Sect. 4.1). This allows for comparison of the equilibrated ice sheet response to a present day climate forcing with independent data on ice sheet geometry (e.g. Bamber et al., 2001), thus highlighting ISM-specific deviations.

Secondly, the pre-industrial control output from the HadAM3 GCM is used to force the ISMs (see Sect. 4.1). The reasoning behind this is twofold; (i) the differences in the modern/pre-industrial climatologies, observed and modelled, are relatively small (see Figs. 1 and 2) and therefore any differences seen in simulated ice sheet extent or

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volume may highlight thresholds or instabilities in the modern reconstruction of the ice sheets, and (ii) any large differences incurred in the equilibrium ice sheet response as a result of using a HadAM3 modelled climatology (rather than observed) may point to potential weaknesses in the ice sheet reconstructions using the same climate model for the Pliocene.

2.1.2 Mid-Pliocene Warm Period simulations (phase 1)

Phase 1 ISM simulations use the climatological forcing from the HadAM3 PlioMIP Experiment 1 results (see Sect. 4.1). Phase 1 simulations as outlined in Table 1 test the sensitivity of the ISMs to initial ice sheet configurations within the ice sheet model, which has an important influence on ice sheet hysteresis (Pollard and DeConto, 2005).

As the ice sheet configurations for the Pliocene are largely unknown, it is difficult to decide with confidence how to initiate the ISMs. Modern ice geometry is almost certainly too large based on sea level records of higher-than-modern sea level (Dowsett et al., 2010). Ice-free conditions with isostatically rebounded bedrock is a possibility for Greenland (Raymo et al. 2011 and references therein) and West Antarctica (Pollard and DeConto, 2009), but not for East Antarctica. The best available approximation for Pliocene ice sheets used as boundary conditions for HadAM3 (PRISM3; Hill, 2009; Haywood et al., 2010) are based on previous modelling studies and may be subject to model-dependent uncertainties. Therefore, we have chosen to initiate the PLISMIP experiments with (i) a maximum envelope of ice sheet geometries, i.e. ice free for Greenland and modern ice for the Antarctic ice sheets, and (ii) an approximation based on the PRISM3 data set (see Table 1). These initial ice sheet configurations are shown in Fig. 3.

2.1.3 Mid-Pliocene Warm Period simulations (phase 2)

Phase 2 further quantifies uncertainties in the simulation of ice sheets in the mPWP, by altering the ice sheet configuration prescribed in the GCM (HadAM3). In the original

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PlioMIP Pliocene HadAM3 simulation, the prescribed ice sheet was based upon the PRISM3 data set. For the reasons outlined in Sect. 2.1.2, this uncertain ice sheet configuration may lead to an over- or underestimation of the climatic forcing appropriate for the mPWP. Therefore, an additional climate model experiment using HadAM3 was performed using PRISM3 boundary conditions, but with ice-free (isostatically rebounded) conditions on Greenland (Fig. 3c) and a modern ice sheet over Antarctica (Fig. 3d). This new climatology provided by the GCM is used to force the ISMs for the Phase 2 experiments (see Table 1).

3 Ice sheet models

As noted above, there are two types of ISM taking part in PLISMIP; shallow-ice approximation and shallow-shelf approximation ISMs (for an overview see Pollard 2010). The shallow-ice approximation (hereafter SIA, Hutter, 1983) to the Stokes equations is a widely adopted, computationally efficient approach to modelling ice sheet flow. The SIA method is valid for ice sheets that have a small aspect ratio and where the bedrock and surface slopes are sufficiently small that the normal components of stress can be neglected (e.g. Bueler and Brown, 2009). SIA considers only horizontal shear stresses, which are concentrated towards the base of the ice sheet and gravity is assumed to be the driver of ice flow. Although the SIA approximation prohibits any representation of higher-order stresses in the ice, it has been shown to perform well compared with full stress models (Leysinger Vieli and Gudmundsson, 2004). SIA ISMs are used in the experiments simulating the Greenland and East Antarctic ice sheets in this project.

Shallow-shelf approximation (SSA) models use a different balance of momentum equations to determine the ice flow. Typically SSA models describe a membrane-type flow with the ice floating or sliding over a weak base. Although SSA models are best applied to ice shelves as there are no shear stresses acting on the base of the floating ice, they can be used on grounded ice if they include additional basal resistance terms or they can be combined with SIA models to provide a single SIA/SSA hybrid

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model (e.g. Bueler and Brown, 2009; Pollard and DeConto, 2007), which is capable of simulating the complete grounded/floating ice sheet/shelf system. In the case of Antarctica, where the buttressing effects of ice shelves are particularly important for the simulation of the West Antarctic Ice Sheet, (WAIS), SSA and SIA/SSA ISMs are used.

4 Ice sheet model simulations set-up and output

4.1 Input climatologies

The NCEP/DOE AMIP-II Reanalysis (NCEP/DOE-2, Kanamitsu et al., 2002), a data assimilation product based on the widely used NCEP/NCAR Reanalysis (NCEP-1), is used as the driving climatology set for the control phase. It features improvements on NCEP-1 by fixing known errors and by updating parameterizations of physical processes including a smoother orography, and a non-local boundary layer parameterization, as well as a new deep convection parameterization. The reanalysis was updated in 2005 and 2008, fixing errors associated with sea ice and the source code. Both NCEP/NCAR-1 and NCEP/DOE-2 have been used to validate climate model results, and importantly for this project, the data are in agreement with other reanalysis products over high latitudes (e.g. Serreze and Hurst, 2000; Kharin et al., 2007). The data are available globally, with a spectral horizontal resolution of T62 and 28 vertical levels. Climate parameters are available up to four times daily from 1979 to the present day.

The GCM climatologies used in this project are provided by the HadAM3 GCM, which has a horizontal resolution of 2.5° in latitude, 3.75° in longitude, and 19 vertical layers in the atmosphere (see Pope et al., 2000 for further details). HadAM3 is the preferred model for PLISMIP, because there is a long history of Pliocene climate simulations using this model (e.g. Haywood et al., 2000, 2002, 2009; Haywood and Valdes, 2006; Hill et al., 2007, 2010; Hill, 2009), and the model is already equipped to run with altered PRISM boundary conditions (as described above in Sect. 1.2).

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Figures 1 and 2 show how the NCEP reanalysis climate differs from the HadAM3 pre-industrial climate over Greenland and Antarctica. HadAM3 is slightly cooler over Greenland (2 to 6 °C), and up to 10 °C cooler over Antarctica. Precipitation rates between the two climatologies are similar over the ice sheet areas. These deviations will be taken into consideration in the analysis of ice sheet model results of modern and Pliocene climates.

The difference between HadAM3 modelled pre-industrial and Pliocene climates can be seen in Figs. 4 and 5. Over Greenland and Antarctica there are mean annual temperature increases in the Pliocene of over 20 °C compared with pre-industrial temperatures over those areas where prescribed Pliocene ice sheet configurations (PRISM3) differ significantly from modern day extents (Fig. 3). In general, the ice sheet regions are also wetter during the mPWP with precipitation increases as high as 0.8 m yr^{-1}, although the southern tip of Greenland receives markedly less precipitation (a reduction of around 0.5 m yr^{-1}) as observed in other Pliocene studies applying HadAM3 runs (e.g. Hill et al., 2010).

4.2 ISM set-up

The ISMs are forced with average annual and monthly temperature and precipitation data sets calculated from climatological means of the NCEP data set and HadAM3 simulations. NCEP data is provided at a grid resolution of $2^\circ \times 2^\circ$. HadAM3 driving fields as well as the PRISM3 land-sea mask and global topography are supplied at the resolution of HadAM3, i.e. on a 73 × 96 global grid.

Standard bedrock topographies for running the ISMs originate from EISMINT (Huybrechts et al., 1996) for the GrIS and from BEDMAP for the Antarctic ice sheets (Lythe and Vaughan, 2001). These data, along with the PRISM3 ice sheet configurations (Fig. 3) are supplied on a 20 km × 20 km grid, which is the preferred ice sheet model resolution for the PLISMIP simulations. All data required to run the ISM simulations are

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available on the PLISMIP website which is hosted at the University of Leeds.[2]

Unlike many previous ISM intercomparison projects (e.g. EISMINT: Huybrechts et al., 1996 and ISMIP-HOM: Pattyn et al., 2008) the different ISMs are set up in standard mode. This methodology was chosen in order to include the uncertainties introduced in ice sheet model predictions by the choice of ice sheet model set up. All ice sheet simulations are initialised with the conditions stated in Table 1. If the ISM is required to start from no ice on isostatically rebounded bedrock, participants are asked to use their own bedrock and rebound model. Where the initial ice sheet is less than modern, the ice sheet configuration along with a rebounded topography in areas where ice is not present is provided.

Lapse rate corrections are to be applied to account for the difference between the surface height in the GCM and the ISM. Corrections are made for temperature fields following the method outlined in Thompson and Pollard (1997). Initially the climate model topography and surface air temperatures are horizontally interpolated to the ISM grid and then the climate model temperature is corrected by:

$$T - \gamma \cdot (Z_{\mathrm{ISM}} - Z_{\mathrm{GCM}}) \quad (1)$$

where T is surface air temperature, Z_{ISM} elevation of the ISM and Z_{GCM} is the climate model elevation, and γ is the uniform lapse rate correction set to 8 °C km^{-1}.

The run length is specified as 30 kyr for Greenland and 100 kyr for Antarctica. If the change in total volume of less than 0.01 % was not reached in 10 000 yr for Antarctica and in 1000 yr for Greenland, the ISMs were extended in steps of 10 000 and 50 000 yr for Greenland and Antarctica, respectively, until the ice sheet come into equilibrium.

[2]https://www.see.leeds.ac.uk/redmine/public/projects/plismip – please contact A. M. Dolan for access to this website.

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4.3 Output

Spatial and temporal output of a number of fields will be required from each ISM. The temporal fields will be used to assess whether the ice sheet has reached equilibrium or is in a state of oscillation. All ISM results will contain time series of grounded ice volume (m^3) and area (m^2) in steps of 100 yr for Greenland and 1000 yr for Antarctica. However, the main focus of the analysis of the project will be on the equilibrium end-member ice sheets submitted for each simulation. For this we request the submission of surface mass balance ($m\,yr^{-1}$ of water equivalent), velocity ($m\,yr^{-1}$), bed elevation (m) and surface elevation (m) fields on the same spatial domains as the gridded input boundary conditions.

5 Conclusions and outlook

This paper provides an overview of the experimental design for the Pliocene Ice Sheet Modelling Intercomparison Project (PLISMIP) which is being undertaken as part of PlioMIP, the latest addition to the PMIP experiments. The project makes use of state-of-the-art ISMs of various complexities to reconstruct the nature and extent of ice sheets of the mid-Pliocene warm period. PLISMIP has the direct intention of quantifying both the uncertainties in ice sheet reconstructions introduced by using a single ISM, as well as the biases that result from a range of assumptions that are necessary to initiate the modelling experiments. Not only will this project shed light into the understanding of palaeo ice sheet variability, but the analysis of the impact of various model uncertainties will help assess the sensitivity of the Greenland and Antarctic ice sheets in a warmer-than-modern world.

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Table 1. Experimental design. Models are run over the three domains of Greenland, East Antarctica, and the whole of Antarctica (including the West Antarctic ice sheet). The control phase corresponds to simulations of present-day/pre-industrial conditions and phases 1 and 2 apply to Pliocene climates. Phase 1 comprises experiments where the initial condition in the ISMs are altered, whereas phase 2 experiments focus on changing the boundary condition prescribed in the climate model. Forcing fields for the ISMs are derived from modelled (HadAM3) and reanalysis data sets (NCEP2). Initial conditions refer to the ice sheet configurations and the topographic state used to initiate the ice sheet modelling experiments.

ISM type	Phase	GCM input	Initial conditions (ISM)		Run ID
			Ice sheet	Topography	
Greenland ice sheet models	Control	Modern-day HadAM3	Modern-day GrIS	Modern	1
	Control	Reanalysis NCEP	Modern-day GrIS	Modern	2
	Phase 1	Pliocene HadAM3, PRISM3 BC	No Ice	Modern (isostatically rebounded)	3
	Phase 1	Pliocene HadAM3, PRISM3 BC	Prescribed PRISM3 GrIS	PRISM3 bedrock	4
	Phase 2	Pliocene HadAM3, PRISM3 BC except no Greenland ice	No Ice	Modern (isostatically rebounded)	5
East Antarctic ice sheet models	Control	Modern-day HadAM3	Modern-day EAIS	Modern	6
	Control	Reanalysis NCEP	Modern-day EAIS	Modern	7
	Phase 1	Pliocene HadAM3, PRISM3 BC	Modern-day EAIS	Modern	8
	Phase 1	Pliocene HadAM3, PRISM3 BC	Prescribed PRISM3 EAIS	PRISM3 bedrock	9
	Phase 2	Pliocene HadAM3, PRISM3 BC except modern EAIS	Modern-day EAIS	Modern	10
Whole of Antarctic ice sheet models	Control	Modern-day HadAM3	Modern-day Antarctica	Modern	11
	Control	Reanalysis NCEP	Modern-day Antarctica	Modern	12
	Phase 1	Pliocene HadAM3, PRISM3 BC	Modern-day Antarctica	Modern	13
	Phase 1	Pliocene HadAM3, PRISM3 BC	Prescribed PRISM3 Antarctica	PRISM3 bedrock	14
	Phase 2	Pliocene HadAM3, PRISM3 BC except modern Antarctica	Modern-day Antarctica	Modern	15

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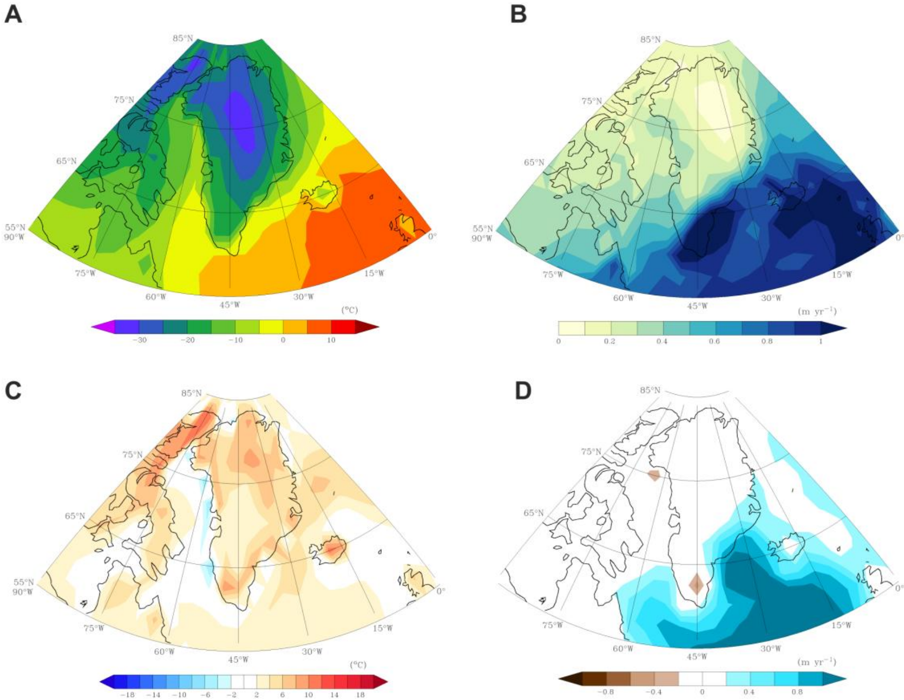

Fig. 1. Control phase driving climatologies. **(A)** HadAM3 modelled mean annual surface air temperature (°C) and **(B)** mean annual precipitation rate (m yr^{-1}) and **(C)** the differences between NCEP reanalysis data and HadAM3 (NCEP-HadAM3) for annual mean surface air temperature (°C) and **(D)** precipitation (m yr^{-1}) over Greenland. Note that NCEP reanalysis data was interpolated to the HadAM3 GCM grid before calculating the differences.

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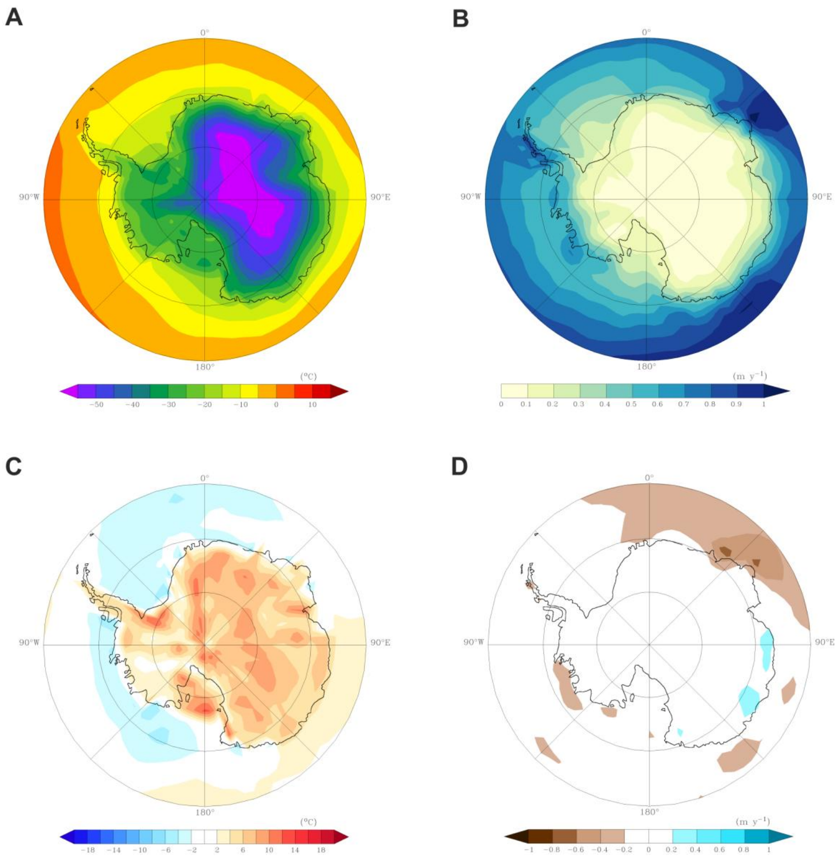

Fig. 2. Control phase driving climatologies. **(A)** HadAM3 modelled mean annual surface air temperature (°C) and **(B)** mean annual precipitation rate (m yr^{-1}) and **(C)** the differences between NCEP reanalysis data and HadAM3 (NCEP-HadAM3) for annual mean surface air temperature (°C) and **(D)** precipitation (m yr^{-1}) over Antarctica.

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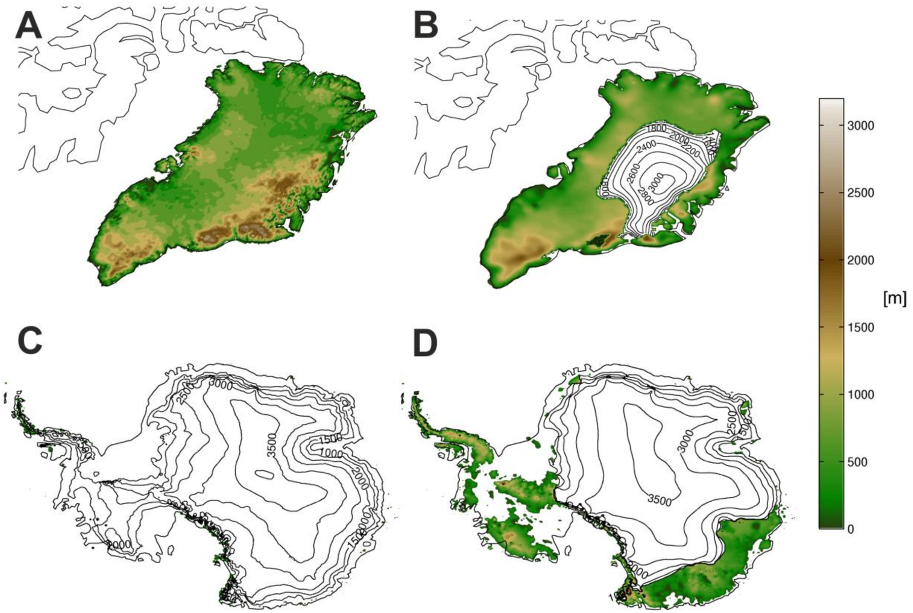

Fig. 3. Ice sheet model initial conditions showing **(A)** an ice free Greenland, **(B)** PRISM3 ice over Greenland (Hill, 2009; Dowsett et al., 2010), **(C)** the modern Antarctic ice sheet topography (m) and **(D)** PRISM3 Antarctic ice.

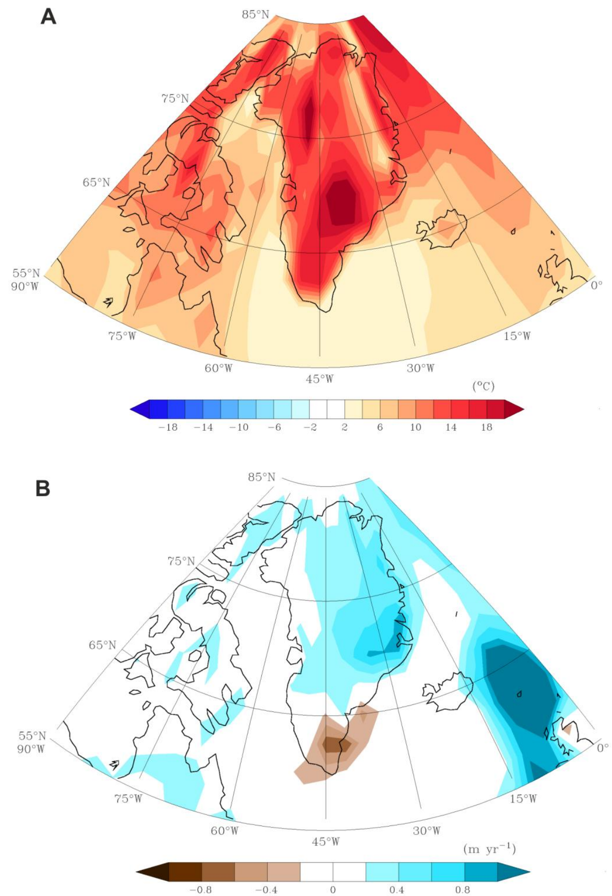

Fig. 4. **(A)** HadAM3 Pliocene minus pre-industrial mean annual surface air temperature (°C) and **(B)** mean annual precipitation rate (m yr^{-1}) anomaly over Greenland.

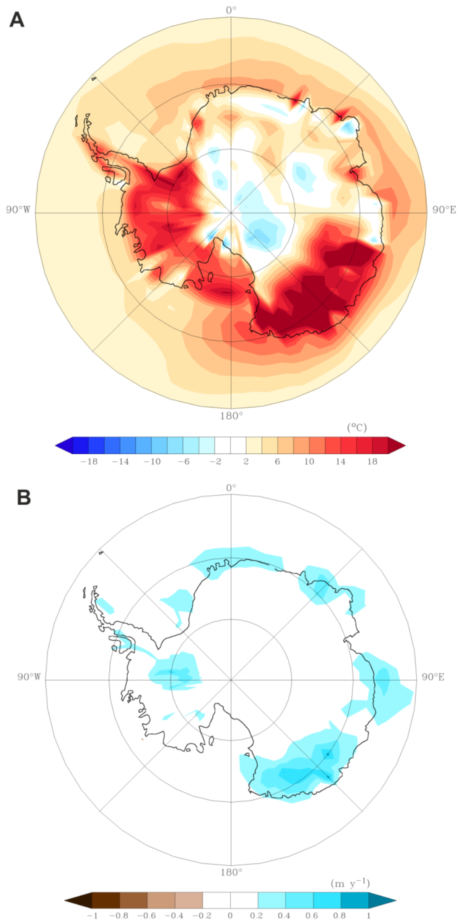

Fig. 5. (A) HadAM3 Pliocene minus pre-industrial mean annual surface air temperature (˚C) and **(B)** mean annual precipitation rate (m yr^{-1}) anomaly over Antarctica.

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