Sensitivity of the Greenland Ice Sheet to Pliocene sea surface temperatures

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ABSTRACT: The history of the GrIS (Greenland Ice Sheet), particularly in warm climates of the pre-Quaternary, is poorly known. IRD (ice-rafted debris) records suggest that the ice sheet has existed, at least transiently, since the Miocene and potentially since as long ago as the Eocene. As melting of the GrIS is a key uncertainty in future predictions of climate and sea-level, understanding its behaviour and role within the climate system during past warm periods could provide important constraints. The Pliocene has been identified as a key period for understanding warmer than modern climates. Detailed micropalaeontological analyses of the mid-Piacenzian Warm Period (3.264 - 3.025 Ma) have produced a series of SST (sea-surface temperature) reconstructions (PRISM2-AVE, PRISM2-MAX, PRISM2-MIN and PRISM3). Use of these different SSTs within the Hadley Centre GCM (General Circulation Model) and BASISM (British Antarctic Survey Ice Sheet Model), consistently show large reductions of Pliocene Greenland ice volumes compared to modern. The changes in climate introduced by the use of different SST reconstructions do change the predicted ice volumes, mainly through precipitation feedbacks. However, the models show a relatively low sensitivity of modelled Greenland ice volumes to different mid-Piacenzian SST reconstructions, with the largest SST induced changes being 20% of Pliocene ice volume or less than a metre of sea-level rise.

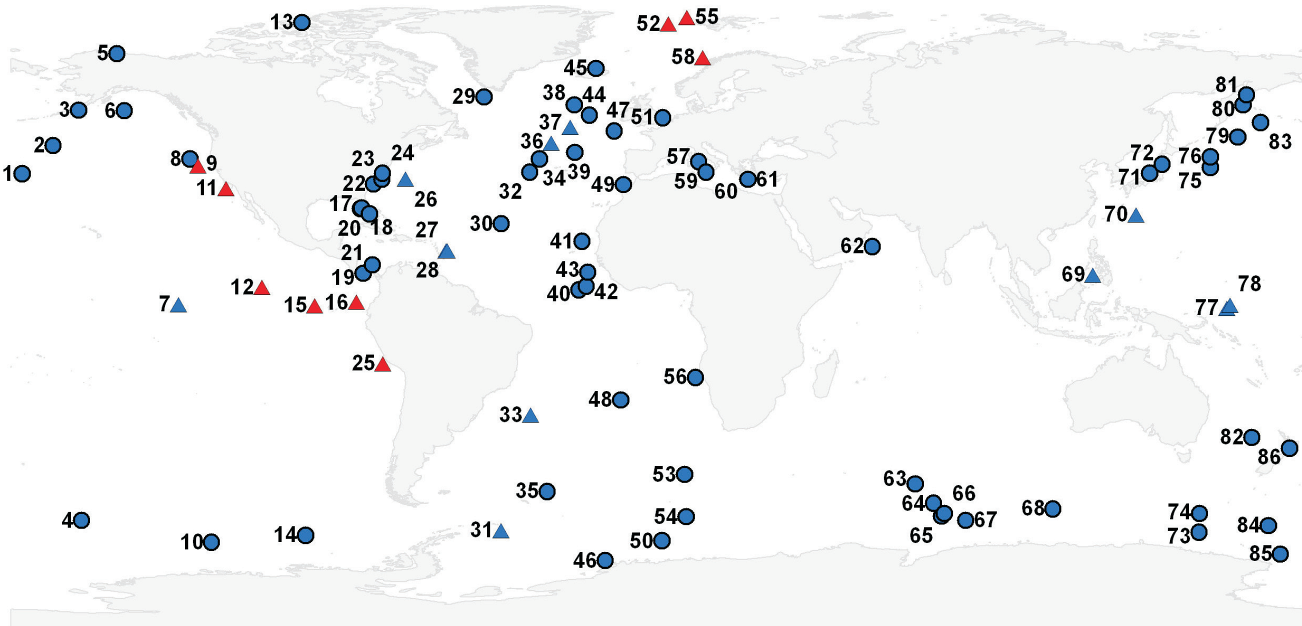
INTRODUCTION

The MPWP (mid-Piacenzian Warm Period; 3.264 - 3.025 Ma) was the last period of sustained warmth, before the intensification of Northern Hemisphere glaciations. Although there will never be a perfect analogue for future climate change, the Pliocene has been identified by many as one of the best and most accessible examples of a palaeoclimate operating at the global mean temperatures predicted for the next century (e.g. Jansen et al. 2007). As such it provides an ideal interval for studying the workings of the climate system under warmer than modern global temperatures. One of the key uncertainties in future predictions of climate and particularly sea level rise is the GrIS (Meehl et al. 2007). An understanding of how Greenland developed an ice sheet and especially how it responded to past periods of global warmth could help inform predictions of its future development. The behaviour of the GrIS is not well known, even for recent periods of the Pleistocene. However, the large volume and quality of palaeoenvironmental data available for the MPWP enables us to produce well-constrained boundary conditions for modelling of this time period. These can provide the necessary temperature and precipitation fields to produce models of the Pliocene GrIS and test its sensitivity to the prescribed SSTs.

GREENLAND ICE SHEET HISTORY

The GrIS is the largest terrestrial ice mass in the Northern Hemisphere, with best estimates suggesting it contains approximately 7.3 metres of sea level equivalent (Bamber, Layberry and Gogineni 2001). At the LGM (Last Glacial Maximum), the extent of the GrIS was expanded around much of its margin, but the advance was generally limited. Only the southern portions expanded onto the continental shelf and only in south-east Greenland did the ice sheet reach the shelf edge (Funder and Hansen 1996; Funder et al. 1998; Solheim et al. 1998). Sea levels at the LGM, only 21,000 years ago, were at least 120m lower than today. However, Greenland contributed only a very small component to this, perhaps 2 – 3m, with North American, Eurasian and probably West Antarctic ice sheets dominating the signal (Bentley 1999; Clark and Mix 2002). Apart from Greenland very little terrestrial ice remains in the Northern Hemisphere, restricted to mountain glaciers and ice caps in the Northern Rockies and the islands of the Arctic. Global estimates of terrestrial ice volumes suggest that mountain glaciers and ice caps contain less than 0.4 metres of potential sea-level rise contributions (Lemke et al. 2007), showing that even small changes to the Greenland and Antarctic ice sheets will quickly dominate future sea-level rise. Modelling studies and ice core data suggest that during the Last Interglacial (the Eemian at 125 ka) the GrIS was reduced compared to modern, but that Greenland was still largely ice covered (Otto-Bleisner et al. 2006; Overpeck et al. 2006). This is the last period for which direct evidence of the state of the GrIS in the past can be found, as any significantly older ice has almost certainly been lost, through basal or marginal melting or iceberg calving.

IRD from marine cores provides an indirect method of examining the palaeo-glaciation of Greenland. Certain clast sizes within marine cores are known to have no transport mechanisms apart from delivery to the site by icebergs (Grobe 1987). Thus their presence in a core indicates iceberg transport of sediment to the site and their abundance is an indicator of the frequency of icebergs passing through the local environment. However, the relationship of iceberg production to the size and evolution of an ice sheet is not straightforward. Polar ice sheets with an ocean interface will produce icebergs, as this is one of the major ice discharge mechanisms that can balance accumulation. In-



TEXT-FIGURE 1
Marine core sites used in the compilation of the PRISM SST reconstructions. Blue sites are included in both the PRISM2 and PRISM3 reconstructions, whereas red sites only appear in PRISM3. Circular sites have only been studied using faunal analysis, but triangular sites include multi-proxy analysis in the PRISM3 reconstruction.

creases in iceberg production can occur in all phases of ice sheet evolution. If the ice sheet is in an equilibrium state, i.e. accumulation and ice loss are balanced, then iceberg production can be increased if there is an equivalent increase in accumulation. An increase in calving, without changes in the other ice sheet mass balance components, would lead to a greater iceberg production and ice sheet retreat. Whereas iceberg production could increase due to an ice sheet advance, as it is likely that the ice – ocean interface would increase in length. The picture is further complicated by the role of internal ice sheet dynamics in iceberg production rates, such as those invoked to explain Heinrich Events (Alley and MacAyeal 1994; Hulbe et al. 2004). However, the presence of IRD does indicate that ice is reaching down to the ocean and producing sufficiently large icebergs to resist ocean melting between the point of origin and the core site.

Northern Hemisphere records of IRD show that large numbers of icebergs have been present in the sub-Arctic seas throughout the Pleistocene glacial-interglacial cycles (Spielhagen et al. 1997; St. John and Krissek 1999; Hiscott et al. 2001; McIntyre, Delaney and Ravelo 2001). There are few records of sufficient length to record periods of the past when no IRD was present. However, all the records that go back as far as the Pliocene epoch show no or at least much lower levels of IRD, followed by a huge increase during the Plio-Pleistocene transition starting at approximately 2.8 Ma (Jansen et al. 2000; Kleiven et al. 2002; Knies et al. 2002; St John and Krissek 2002). On the Greenland continental shelf, where there is little opportunity for melting between potential calving sites and the drill sites, glaciomarine diamictites, dropstones and IRD have been found from as long ago as the Miocene, 7 million years ago. The record shows major fluctuations between glacially influenced sedimentation punctuated with periods with no evidence for glaciation (Larsen et al. 1994). This suggests that Greenland contained a significant body of ice throughout some, though not all, of the late Miocene and Pliocene, although the modern island-wide ice sheet probably didn't form until after the MPWP. A number of recent papers have reported finding Arctic IRD and glacial drop-stones in the Eocene (Moran et al. 2006; Stickley et al. 2009) and into the Oligocene (Eldrett et al. 2007; Tripati et al. 2008). While these have been speculated to be of Greenland origin, it is possible that these deposits could have come from sea-ice or high-Arctic mountain glaciers. They are also probably related to the coldest periods of these epochs and represent short-lived limited-area glacial events.

PRISM SST RECONSTRUCTIONS

As there are no direct methods by which to infer Greenland ice volumes before the Pleistocene, what is required to reconstruct the history of the GrIS through warm periods of the past are accurate palaeoenvironmental reconstructions. If these are used to drive climate models which produce estimates of Greenland temperatures and precipitation, then this information can be used to predict Greenland ice volumes and extent with an ice sheet model. One particularly successful palaeoenvironmental reconstruction has been, and continues to be, the US Geological Survey PRISM project (Pliocene Research, Interpretation and Synoptic Mapping). The PRISM reconstruction represents the most complete series of warmer than modern palaeoclimate reconstructions and incorporates more than a million individual measurements.

PRISM pioneered the concept of a timeslab, defining the mid-Piacenzian warm period (MPWP, previously mid-Pliocene) as the interval between 3.264 and 3.025 Ma. This interval is identifiable in most marine cores, due to distinctive magneto- and bio-stratigraphy (Dowsett et al. 1994). It is also climatically distinct, with oxygen isotopes being lighter than both the intervals immediately before and after and generally considered to be the most recent extended period (over multiple glacial-interglacial cycles) with average $\delta^{18}O$ values higher than modern (Dowsett and Robinson 2006). Long integrated records of Pliocene $\delta^{18}O$ show that the MPWP has similar values to large parts of the Pliocene, particularly the warm Zanclean Stage (5.332 – 3.6 Ma), despite the presence of an apparently strong glacial, KM2 (Lisiecki and Raymo 2005).

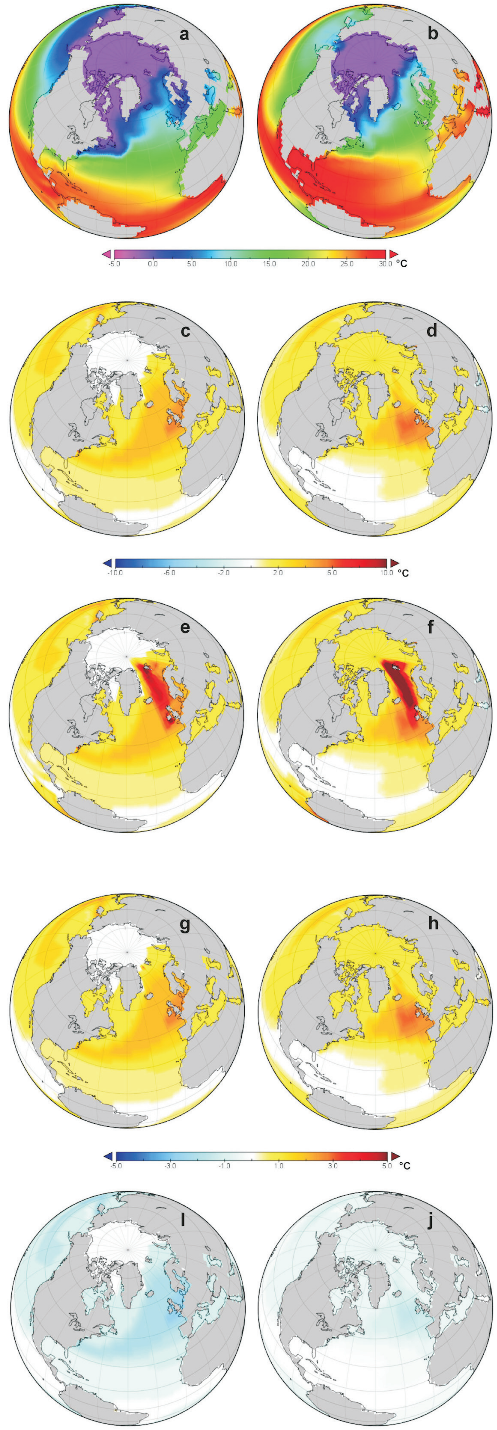
Within the MPWP the PRISM group employed a warm peak-averaging technique to produce their SST reconstructions (Dowsett and Poore 1990). Previous PRISM reconstructions have been integrated into GCM (General Circulation Model) experiments from a select few modelling groups (Chandler, Rind and Thompson 1994; Sloan, Crowley and Pollard 1996; Haywood, Valdes and Sellwood 2000), The latest iteration of the PRISM reconstruction PRISM3D will be incorporated into many more through the PlioMIP (Pliocene Model Intercomparison Project) experiments (Haywood et al. 2010).

PRISM3 incorporates a number of improvements on the previous reconstruction, PRISM2. The first improvement was to re-examine the previously collected data from all 77 of the PRISM2 marine sites (text-figure 1) and produce the PRISM2-MIN and PRISM2-MAX datasets (Dowsett et al. 2005). The original PRISM2 (PRISM-AVE) data is based on the average peak interglacial values, while the PRISM2-MIN represents the lowest peak interglacial values and PRISM2-MAX the highest peak interglacial values (that meet communality statistical tests). The combination of these three reconstructions provides a unique estimate of variations in SST conditions through the interglacials of the mid-Piacenzian. Subsequently, the PRISM dataset has been improved by multi-proxy analysis, adding Mg/Ca and alkenone-based SSTs to existing faunal analysis techniques, and the inclusion of more sites to produce the PRISM3 SST reconstruction. New marine core data from the Arctic Ocean (Robinson 2009), sub-polar North Atlantic (Robinson et al. 2008) and equatorial Pacific (Dowsett 2007; Dowsett and Robinson 2009) provide significant improvements in these previously data sparse regions (text-figure 1). This provides us with four different Pliocene SST reconstructions for use in the Hadley Centre GCM (text-figure 2).

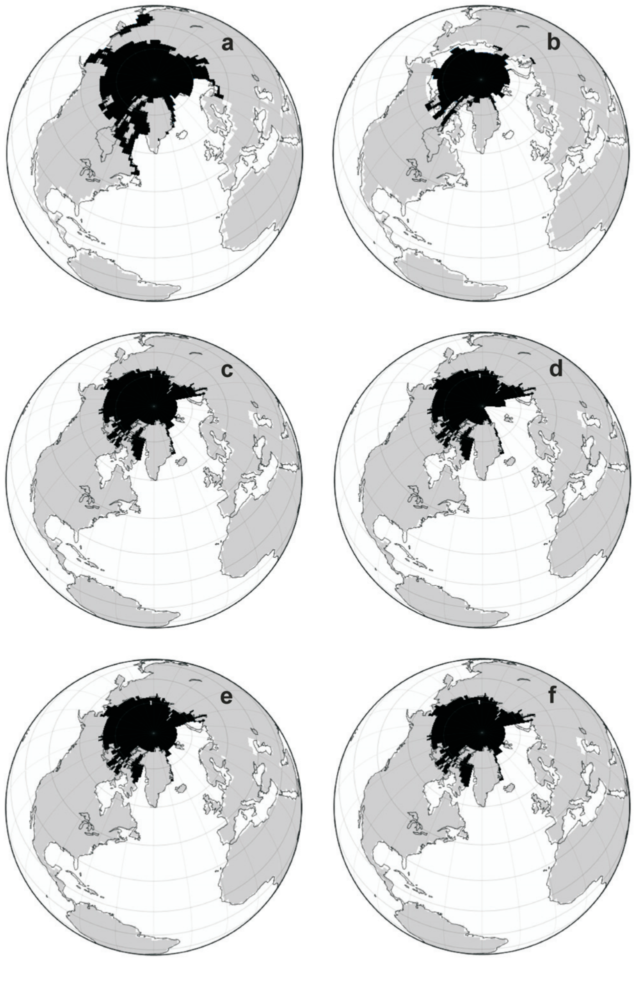
MODEL DESCRIPTIONS

The UK Met Office HadAM3 (Hadley Centre Atmosphere-only GCM)

The HadAM3 GCM was used throughout this study. The model runs on a global 73 × 96 grid, giving a horizontal resolution of 2.5° in latitude and 3.75° in longitude, with 19 vertical layers in the atmosphere and a time step of 30 minutes (Pope et al. 2000). It includes a radiation scheme that represents the effects of minor trace gases (Edwards and Slingo 1996) and a parameterized background aerosol climatology (Cusack et al. 1998). The model uses the convection scheme of Gregory, Kershaw and Inness (1997) and the land-surface scheme includes soil moisture freezing and melting. The representation of evaporation in-



TEXT-FIGURE 2
Various SST reconstructions used in this modelling study. The first row depicts the modern SSTs using the same techniques as the other PRISM reconstructions, in (a) February and (b) August. (c) February and (d) August SSTs in the PRISM2-AVE SSTs, as an anomaly from modern. The full twelve month SSTs used in the experiments are derived from these two reconstructions, with a sine curve providing the temporal interpolation. (e) February and (f) August differences between PRISM3 and modern SSTs. (g) February and (h) August PRISM2-MAX anomalies from PRISM2-AVE and (i) February and (j) August PRISM2-MIN anomalies. Note the different scales for the final four panels, showing much lower differences between different PRISM2 SST reconstructions than from modern.



TEXT-FIGURE 3
PRISM sea-ice fields, derived from the different SST reconstructions. (a) February and (b) August modern sea-ice fields. February sea-ice reconstructions are shown for (c) PRISM2-AVE, (d) PRISM3, (e) PRISM2-MAX and (f) PRISM2-MIN. Pliocene August sea-ice reconstructions are not shown, because for each there is no Arctic sea-ice.

cludes the dependence of stomatal resistance on temperature, vapour pressure and CO_2 concentration (Cox et al. 1999). HadAM3 has been used extensively for modern, future and palaeoclimate experiments, having been shown to perform well against modern and past climate data (Slingo et al. 1999; Haywood et al. 2000; Pope et al. 2000).

BASISM (British Antarctic Survey Ice Sheet Model)

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, according to Method 1 of Hindmarsh and Payne (1996). This scheme maintains numerical stability for long time steps, by setting the implicitness factor, $\infty \geq n/2$ (Hindmarsh 2001), enabling multi-millennial experiments. The temperature dependent rate factor is modelled by a dual-Arhenius relationship (Hindmarsh and Le Meur 2001). Vertical discretization is at layers of constant fractional depth (Huybrechts and Oerlemanns 1988), i.e. where ζ is constant. Vertical advection is modelled using a MacAyeal-Hulbe equation, generalized to include flow by internal deformation (Hindmarsh 1999; Hulbe and MacAyeal 1999). This numerical scheme has yet to be extended to include the more complex flow regimes of ice streams and ice shelves, as the understanding of the physics and implementation of new physics in these regimes is incomplete.

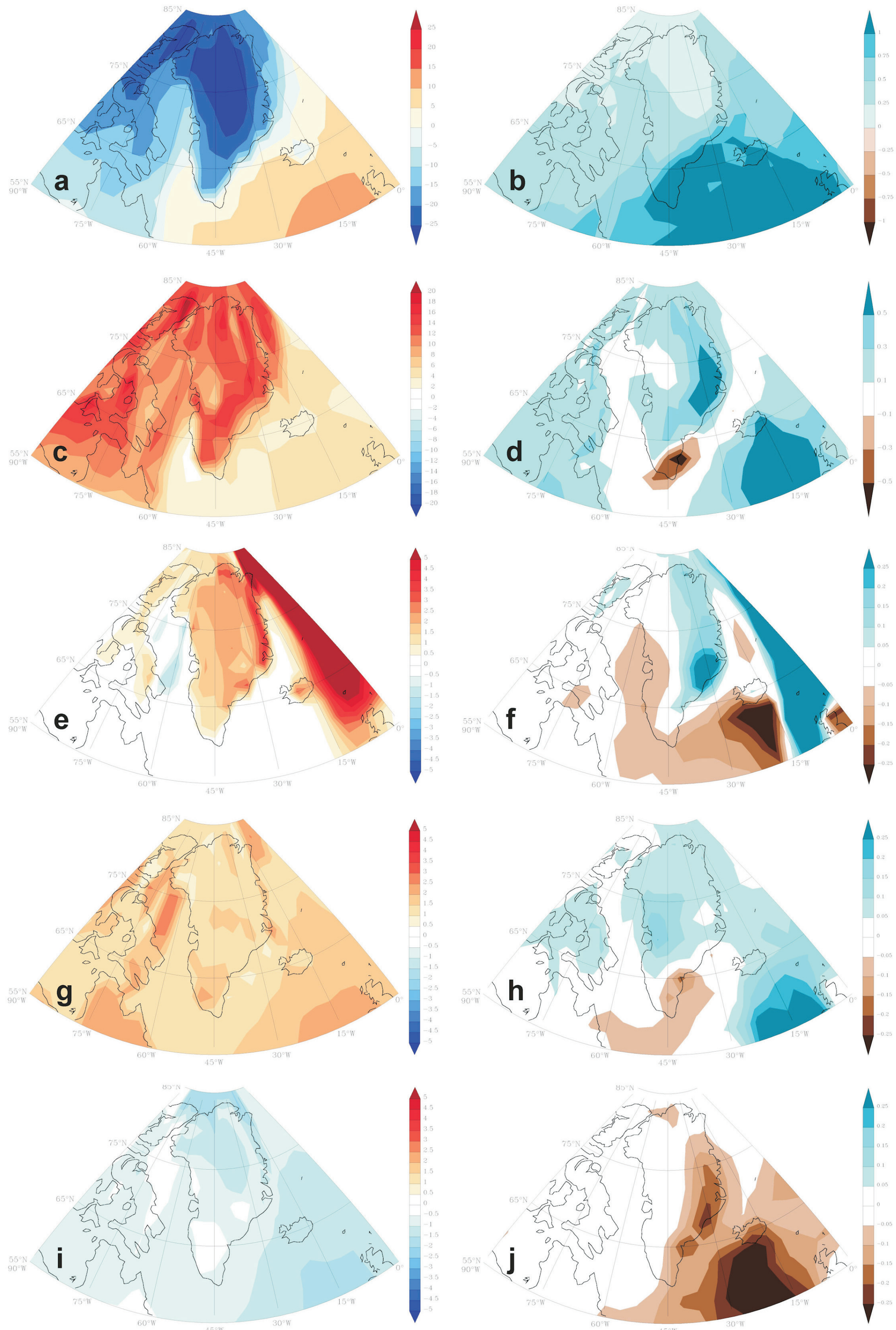
BASISM was run on a 20km × 20km grid, with 21 vertical layers, in a domain covering the modern grounded Greenland Ice Sheet (Letreguilly, Huybrechts and Reeh 1991). The GCM is run on a much coarser grid and hence output climate fields require downscaling onto the Ice Sheet Model grid. The relevant fields from the GCM model were downscaled using a bilinear interpolation technique and simple lapse rate correction. The PDD (Positive Degree-Day) method was then employed to convert these climate fields into an accumulation / melt rate (Reeh 1991; Braithwaite 1995). This technique assumes that the melting of the ice sheet surface can be fully described by three physical constants and the temperature record, which, although many other factors could contribute, has been shown to have some physical justification (Ohmura 2001). As the change in the temperature – melt relationship over time is unknown the range of PDD parameters (5-14 for ice and 3-6 for snow) observed under different modern day climates (Braithwaite 1995), from alpine glaciers to polar ice caps, are used for each GCM climatology. The ice sheet model was also run with a range of initial ice sheet configurations, ranging from no ice to the modern GrIS, in order to include any hysteric effect of altitude-temperature feedbacks on final, equilibrium ice sheet volumes.

GCM Experimental Design

Five different HadAM3 GCM experiments are used in this study. A modern experiment, MODERN, was run using the GISST modern SST reconstruction, covering the period 1961-1990 (Parker, Folland and Jackson 1995). Topography and ice-cover are derived from the US Navy data sets (Jasperson et al. 1990) and vegetation from W&HS85 (Wilson and Henderson-Sellers 1985) land cover scheme. Atmospheric trace gases are set to pre-industrial levels of 280 ppmv of CO_2 and 760 ppbv of methane.

All the Pliocene experiments use the full PRISM2 boundary conditions. The PRISM palaeoenvironmental reconstruction includes SSTs, sea-ice extent, global vegetation, orography, ice sheets, sea level and land-sea distribution. Vegetation is based on Pliocene data from 74 sites distributed across the globe. Each global land grid point was assigned to one of seven biome classifications (ice, tundra, coniferous forest, deciduous forest, grassland, rainforest and desert). In regions where no Pliocene data was available modern vegetation distribution was used (Thompson and Fleming 1996). The soil parameters needed by HadAM3 experiments are derived from the soil types typical of each vegetation class, as part of the implementation of the PRISM biomization.

Orography is largely unchanged in the Pliocene. However, the PRISM2 reconstruction includes a 50% reduction in the height of the Rockies, an increase of 500m in the East African rift system and differences due to ice sheet changes (Dowsett et al. 1999). PRISM2 ice sheets were based largely on sea level records, with a 50% reduction in Greenland ice volumes and a 33% reduction in Antarctic ice. Sea level is reconstructed at 25m above modern, based on number of sea level records, each



TEXT-FIGURE 4

Greenland temperature and precipitation fields for each of the GCM experiments used in this study. (a) absolute temperature and (b) precipitation in MODERN experiment. (c) temperature and (d) precipitation in PRISM2^{AVE} as a difference from modern. Changes in (e) temperature and (f) precipitation in the PRISM3^{SST} experiment from PRISM2^{AVE}. (g) temperature and (h) precipitation anomaly in PRISM2^{MAX} from PRISM2^{AVE}. (i) temperature and (j) precipitation in PRISM2^{MIN} as an anomaly from PRISM2^{AVE}. All temperatures are in degrees Celsius and all precipitation values are in metres per year. See Table 1 for boundary conditions used in the various GCM experiments.

TABLE 1
Boundary conditions for the different GCM experiments used in this study. GCM parameters not included in this table were kept at modern values throughout all the experiments.

HadAM3 Experiment	SSTs, sea-ice & LSM (land-sea mask)	Sea-ice leads	Vegetation & soils	Ice Sheets & orography	Atmospheric CO_2 (ppmv)
MODERN	GISST (1961-1990)	0.05	W&HS85	US Navy	280
PRISM2^{AVE}	PRISM-AVE	0.1	PRISM2	PRISM2	405
PRISM2^{MAX}	PRISM-MAX	0.1	PRISM2	PRISM2	405
PRISM2^{MIN}	PRISM-MIN	0.1	PRISM2	PRISM2	405
PRISM3^{SST}	PRISM3	0.1	PRISM2	PRISM2	405

with significant uncertainty, but with best estimates in agreement (Dowsett and Cronin 1990; Wardlaw and Quinn 1991; Kennett and Hodell 1993). Subsequent records of mid-Piacenzian sea level seem to support 25m of sea level rise (Dwyer and Chandler 2009; Naish and Wilson 2009). The land-sea distribution was changed from land in the modern to ocean in all areas that today are below the 25m reconstructed sea level rise.

Four different Pliocene experiments are used in this study. PRISM2^{AVE}, PRISM2^{MAX} and PRISM2^{MIN} represent the various PRISM2 peak Pliocene SST reconstructions, PRISM2-AVE, PRISM2-MAX and PRISM2-MIN, respectively and utilise all the other PRISM2 boundary conditions. PRISM3^{SST} includes the latest SST reconstruction, but the other boundary conditions remain as PRISM2. Evidence suggests that the Arctic was ice-free during Pliocene summers (Cronin et al. 1993), so this provides one extreme for sea-ice reconstructions. There is little or no data on winter Arctic sea-ice distributions, so these are based on the SST reconstructions and thus also change between the various experiments (text-figure 3). Sea-ice leads are increased in the Pliocene, reflecting the expected change in the nature of sea-ice, from significant volumes of multi-year ice to annual sea-ice formation.

Pliocene CO_2 values are set to 405 ppmv, as specified in PlioMIP (Haywood et al. 2010), in agreement with most of the proxy records (Kürschner et al. 1996; Raymo at el. 1996; Pagani et al. 2009; Seki et al. 2010). While the absolute value and range of Pliocene CO_2 concentrations still has significant uncertainty, the specification of realistic Pliocene SSTs in HadAM3 means that most of the temperature effect will have been incorporated in the models. For example, original HadAM3 experiments were done with a CO_2 concentration of 315 ppmv (Haywood et al. 2000) rather than the 405 ppmv specified here, with differences of only 0.2°C in global mean temperature. Other boundary conditions, such as other atmospheric trace gases and orbital parameters, were set to modern interglacial values, but model sensitivity to these parameters is much reduced as SSTs are fixed. All the changes to the models are outlined in Table 1.

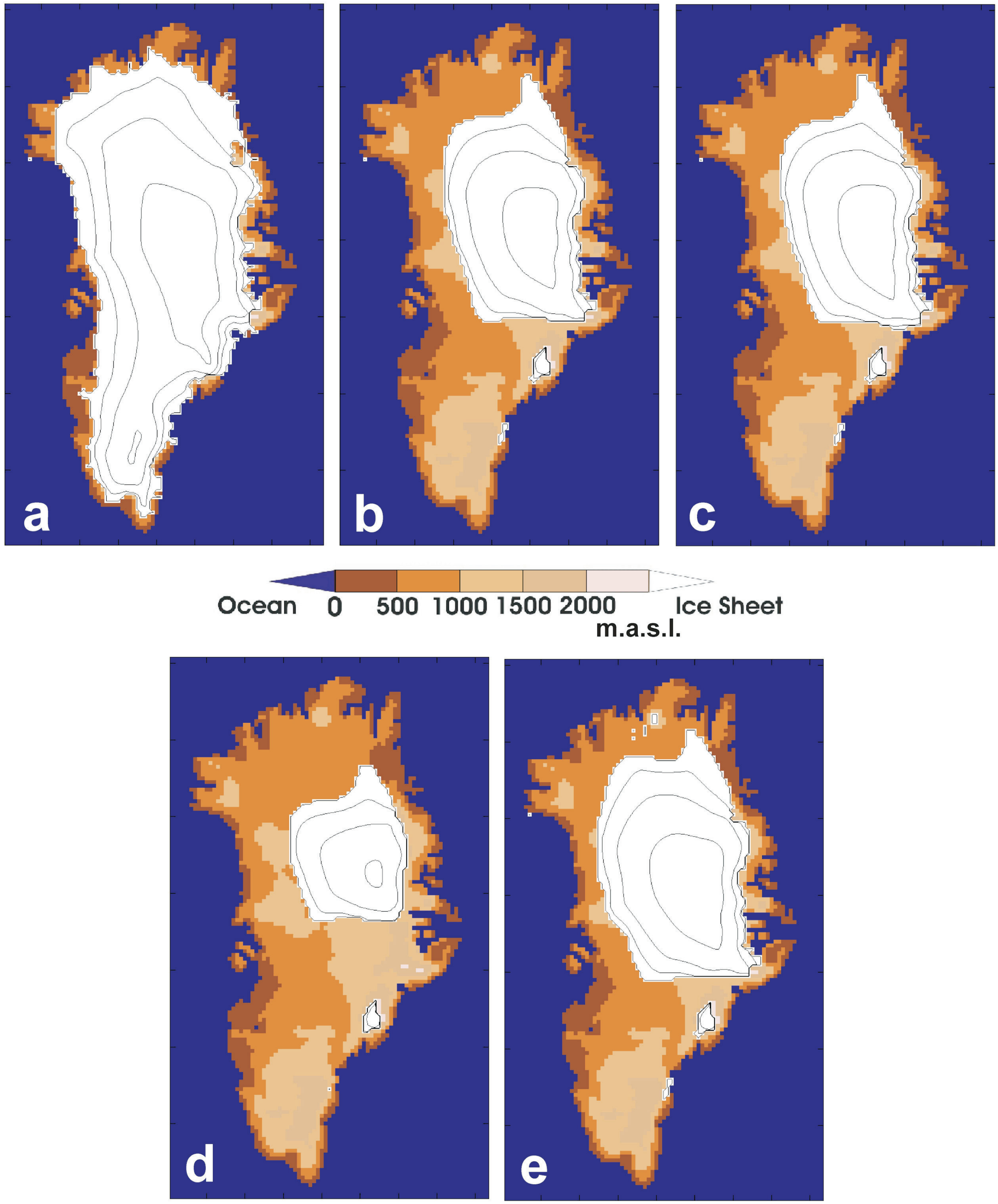
PLIOCENE CLIMATE RECONSTRUCTIONS

Despite using a number of different SST conditions within the Hadley Centre GCM in order to represent the plausible range of peak mid-Piacenzian warmth, the models show many consistent features (Text-figure 4). In all of the models the global average temperatures show a significant increase compared to modern, ranging from +2.61 to +3.32 °C. This consistent response is also seen over Greenland, where polar amplification and change in the prescribed ice sheet leads to increases in average temperature from +10.23 to +14.42 °C. As would be expected global average precipitation also increases, ranging from +0.10 to +0.15 mm/day greater than modern. Regional precipitation patterns in a warmer climate are less predictable, but again the models consistently show increases in average Greenland precipitation of +0.56 to +0.90 mm/day. The PRISM-MAX and PRISM-MIN SSTs cause potentially significant changes in the Greenland climate, typically around 1°C warming or cooling and 0.2 mm/day greater or lesser precipitation respectively. The PRISM3 SSTs introduce a larger change in annual mean Greenland climate, with warming over the whole of Greenland and a large increase in precipitation compared to PRISM2^{AVE} over eastern Greenland.

PLIOCENE GREENLAND ICE SHEET RECONSTRUCTIONS

The PRISM2 experiments give an indication of the range of possible peak warm climates during the mid-Piacenzian and their impact on the GrIS. The PRISM2^{AVE}, PRISM2^{MAX} and PRISM2^{MIN} ice sheets all show remarkably similar configurations, with the vast majority of the ice centred over the mountains of East Greenland (text-figure 5). From this high-altitude accumulation centre the ice sheet is able to expand into some low-lying areas of central Greenland, but never reaches the western or northern coasts. The south of Greenland also has mountains that could act as accumulation areas. However, the climate is too warm in this region to allow significant accumulation of ice. The reduction of the GrIS compared to modern is driven by increases in surface melt in the warmer temperatures of the Pliocene. However, the ice volume differences between models of the MPWP GrIS are largely driven by the differences in precipitation. Thus the warmest climate, PRISM2^{MAX}, produces the largest ice sheet and the coldest climate, PRISM2^{MIN}, produces the smallest GrIS.

Recent additions to the PRISM data set have led to the release of the PRISM3 SST reconstruction (Dowsett, Robinson and Foley 2009). These introduce significant warmer SSTs in the sub-Arctic / northernmost Atlantic (Robinson 2009; Robinson et al. 2008). This temperature signal is much reduced over inland Greenland, but the annual mean change is still larger than be-



TEXT-FIGURE 5
BASISM reconstructions of the Pliocene Greenland Ice Sheet. (a) MODERN, (b) PRISM2^{AVE}, and (c) PRISM3^{SST}, using the best estimates of modern Greenland melt parameters. (d) smallest modelled Pliocene GrIS from PRISM2^{MIN}, using the highest PDD parameters. (e) largest modelled GrIS from PRISM2^{MAX}, using the lowest melt parameters. Plotted ice sheet surface contours are at 3500, 3000, 2500, 1000 and 0 metres above sea level.

tween other Pliocene experiments and is associated with relatively large increases in precipitation in the accumulation areas of eastern Greenland (text-figure 4). However, the changes in annual mean climate do not seem to translate into significant changes in the ice sheet, with the PRISM3^{SST} ice sheets being the closest to the PRISM2^{AVE} (text-figure 5). The main reason for this is that the summer climates of PRISM2^{AVE} and PRISM3^{SST} are remarkably similar over Greenland, so the modelled ice sheet melt does not significantly increase. In fact, the associated increases in precipitation lead to a slight increase in ice volumes in the PRISM3^{SST} case.

For an inland ice sheet, as the predictions suggest typified Greenland during the MPWP, only temperature-driven melt and precipitation-driven accumulation force the mass balance. One of the primary mediators of the climatic sensitivity of an ice sheet is the topography on which the ice sheets sits. The Pliocene climate models presented here are too warm over southern Greenland to allow accumulation over the high ground here, so ice sheet growth only occurs over the mountains of east Greenland. The steep nature of this high-ground and the subsequent steep-sided ice sheet that forms over the region mean that the size of the accumulation and melt areas are largely insensitive to changes in temperature. However, the precipitation that falls in these accumulation areas can still have an impact on the predictions of ice sheet volume and hence seem to be the primary driver in differences between the various Pliocene models.

In these model reconstructions, the Greenland Ice Sheet is not sensitive to the version of the PRISM SSTs prescribed in the model. However, it should be noted that the sensitivity of the ice sheet is temperature dependent, as different accumulation areas can be activated (e.g. southern Greenland) and different topographic profiles can have a large impact (e.g. if accumulation began on the large low-lying regions of Greenland). As temperatures and precipitation from only one GCM, within only one melt parameterization and ice sheet model have been used in this study, it is worth noting that the model dependency of ice sheet sensitivity has yet to be tested. However, the similarity of these reconstructions to previous Pliocene ice sheet experiments, using different models (GLIMMER ice sheet model and the coupled ocean-atmosphere GCM, HadCM3) to test the cause of reduced Pliocene ice volumes (Lunt et al. 2008), give us confidence that model dependency could be low.

CONCLUSIONS

Extensive micropalaeontological research from the USGS PRISM group has produced a series of mid-Piacenzian SST reconstructions unrivalled by any other warmer-than-modern time period. Use of these with the Hadley Centre GCM provides us with a range of plausible climates for the peak warmth during the mid-Piacenzian, from which we can predict an equilibrium ice volume for the GrIS. Whichever climatology is used and whatever the choice of melt parameters (within the bounds of modern-day observations), the GrIS shows significant retreat compared to modern. Differences between the models are relatively small, being largely driven by changes in precipitation. This shows that, at least for these particular models, the reduction in Greenland ice volumes is a robust result and the sensitivity of the GrIS to SSTs in the Pliocene is low.

Each of the different reconstructions gives a significant contribution from Greenland to the mid-Piacenzian sea level of 25m above modern. This ranges from 4.1 to 6.8m (text-figure 6), depending largely on the melt parameters chosen, but also on the SSTs used as a boundary condition within the GCM. While the timescales and many of the boundary conditions would be different when examining future climate change, this result suggests that models of future ice sheet retreat in Greenland (Greve 2004; Alley et al. 2005; Gregory and Huybrechts 2006) are not in conflict with records of Greenland's past behavior.

The model dependency of these results has not currently been examined. However, future work is underway to examine this. PlioMIP will investigate the model dependency of the climate models, with many modelling groups from across the world participating (Haywood et al. 2010). Furthermore, there will be an ice sheet modelling component of the project investigating the model dependency of the ice sheet reconstructions.

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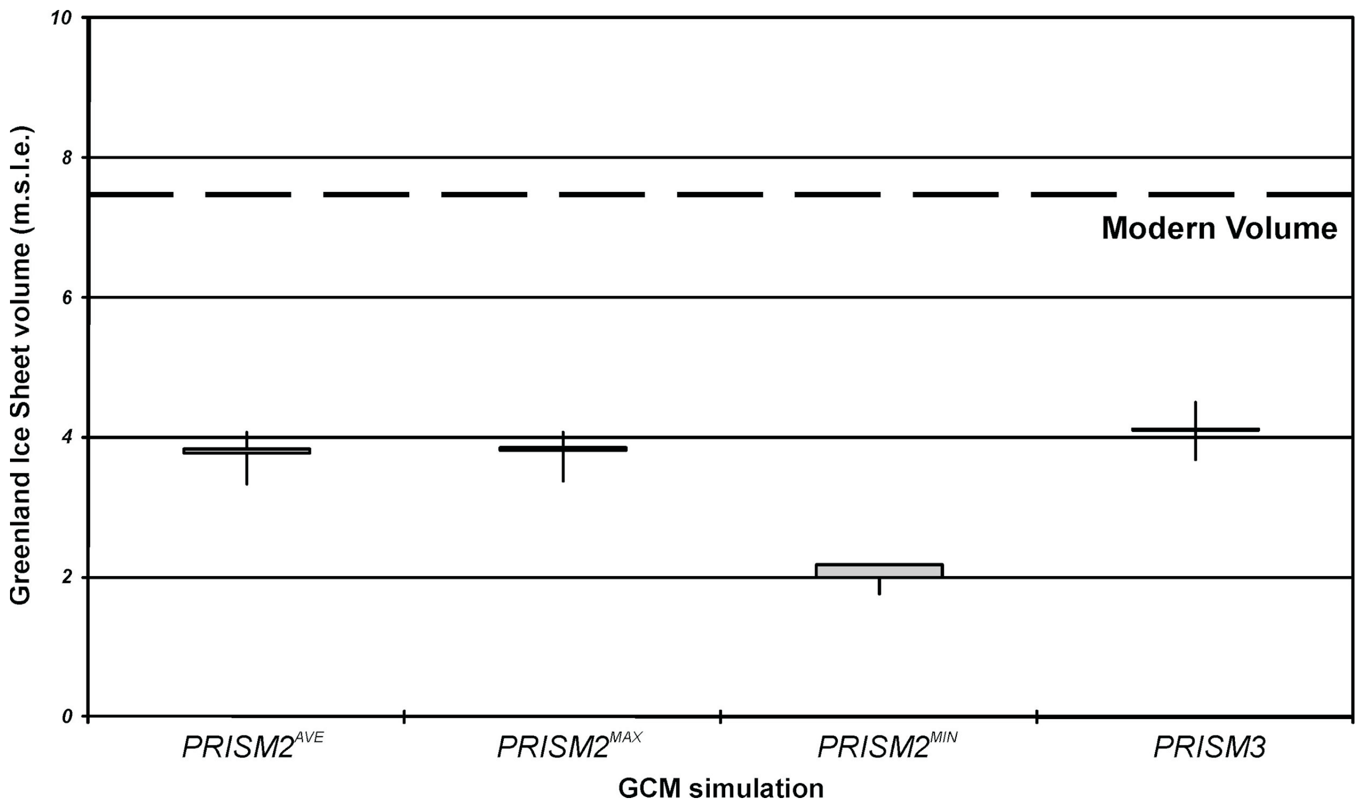

TEXT-FIGURE 6
Range of ice volumes predicted for each Pliocene GCM experiment. The thick bars represent uncertainties due to the initial conditions within the ice sheet model, while thin bars represent uncertainty due to melt parameters. The modern volume depicted on the graph is based on the modelled ice sheet from our MODERN experiment.

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