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Greenland Ice Sheet sensitivity and sea level contribution in the mid-Pliocene warm period – Pliocene Ice Sheet Model Intercomparison Project PLISMIP

S. J. Koenig¹, A. M. Dolan², B. de Boer^{3,4}, E. J. Stone⁵, D. J. Hill^{2,6},
R. M. DeConto¹, A. Abe-Ouchi^{7,8}, D. J. Lunt⁵, D. Pollard⁹, A. Quiquet^{10,*}, F. Saito⁸,
J. Savage⁶, and R. van de Wal⁴

¹Department of Geosciences, University of Massachusetts, 611 N. Pleasant St, Amherst, MA 01003, USA

²School of Earth and Environment, Earth and Environment Building, University of Leeds, Leeds, LS2 9JT, UK

³Department of Earth Sciences, Faculty of Geosciences, Utrecht University, Budapestlaan 4, 3584 CD Utrecht, the Netherlands

⁴Institute for Marine and Atmospheric research, Utrecht (IMAU), Utrecht University, P.O. Box 80005, 3508 TA Utrecht, the Netherlands

⁵School of Geographical Sciences, University of Bristol, University Road, Bristol, BS8 1SS, UK

⁶British Geological Survey, Keyworth, Nottingham, UK

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⁷Atmosphere and Ocean Research Institute, The University of Tokyo, Kashiwa, 277-8568, Japan

⁸Japan Agency for Marine-Earth Science and Technology, Yokohoma 236-001, Japan

⁹Earth and Environmental Systems Institute, Pennsylvania State University, University Park, PA 16802, USA

¹⁰UJF – Grenoble 1/CNRS, Laboratoire de Glaciologie et Géophysique de l'Environnement (LGGE) UMR5183, Grenoble, 38041, France

*now at: Department of Geography, University of Cambridge, Cambridge, CB2 3EN, UK

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Correspondence to: S. J. Koenig (koenig@geo.umass.edu)

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Abstract

The understanding of the nature and behavior of ice sheets in past warm periods is important to constrain the potential impacts of future climate change. The mid-Pliocene Warm Period (2.97 to 3.29 Ma) has global temperatures similar to those projected for future climates, nevertheless Pliocene ice locations and extents are still poorly constrained. We present results from the efforts to simulate mid-Pliocene Greenland ice sheets by means of the international Pliocene Ice Sheet Modeling Intercomparison Project (PLISMIP). We compare the performance of existing numerical ice sheet models in simulating modern control and mid-Pliocene ice sheets by a suite of sensitivity experiments guided by available proxy records. We quantify equilibrated ice sheet volume on Greenland, identifying a potential range in sea level contributions from warm Pliocene scenarios. A series of statistical measures are performed to quantify the confidence of simulations with focus on inter-model and inter-scenario differences. We find that Pliocene Greenland ice sheets are less sensitive to differences in ice sheet model configurations and internal physical quantities, than to changes in imposed climate forcing. We conclude that Pliocene ice was most likely to be limited to highest elevations in East and South as simulated with the highest confidence and by synthesizing available regional proxies, although extents of those ice caps need to be further constrained by using a range of GCM climate forcings.

1 Introduction

One of the largest uncertainties in predicting future climate change is associated with the response of the ice sheets. Instrumental records in the vicinity of the Greenland Ice Sheet (GrIS) show anomalous changes in surface temperatures from pre-industrial to modern (Box, 2002). These, along with recent satellite data and surface mass balance calculations (Box, 2004; Mote, 2007; Rignot et al., 2008; Bhattacharya et al., 2009; van den Broeke et al., 2009; Mernild et al., 2011; Rignot et al., 2011; Shepherd

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et al., 2012), indicate that high-latitude ice sheet-climate environments are particularly sensitive to change, and to anthropogenic warming in particular.

Continental ice sheets can respond to imposed forcings on up to multi-millennial timescales, which limits the ability to predict cryospheric stability based solely on inter-annual to decadal variability from instrumental records. Recent modelling studies have focused on the long-term response of the GrIS to elevated greenhouse gas levels. Simulations show that under potential anthropogenic warming scenarios, the GrIS will disintegrate within a few thousand years (Berger, 2002; Gregory et al., 2004; Ridley et al., 2005; Vizcaíno et al., 2008; Stone et al., 2010; Huybrechts et al., 2011). Moreover, a hierarchy of models predict significant reductions of grounded ice on Greenland, even if $p\text{CO}_2$ levels are stabilized at modern levels (Loutre, 1995; Huybrechts and de Wolde, 1999; Greve, 2000; Gregory et al., 2004). A direct consequence of complete disintegration will be a global-average sea level rise of about 7 m, as inferred from present-day volumetric calculations (Bamber and Aspinall, 2013) and modeling work (Alley et al., 2005). The potential loss of the ice sheet raises questions regarding the strength of ice sheet hysteresis (see Calov and Ganopolski, 2005; Pollard and DeConto, 2005; Fyke et al., 2010; Koenig et al., 2014) and the possibility that the ice sheet will not reform (regrowth potential) once it is lost (Crowley and Baum, 1995; Lunt et al., 2004; Toniazzo et al., 2004; Ridley et al., 2010; Dowsett et al., 2012; Stone and Lunt, 2013). Studies of palaeo-variations of GrIS can contribute to the understanding of these issues and the envelope of its behavior in future warmer climate scenarios.

Palaeoclimatic studies of proxy records (Dahl-Jensen et al., 1998; Cuffey and Marshall, 2000; Johnsen et al., 2001; Rasmussen et al., 2006; Overpeck et al., 2006) and numerical modelling (Otto-Bliesner et al., 2006; van de Berg et al., 2011; Helsen et al., 2013) of the past few interglacials confirm that GrIS has a large sensitivity to high-latitude warming. The mid-Piacenzian or mid-Pliocene warm period (3.29 and 2.97 Ma) has been identified as a potential past climate of high commonality to projected future warming (Haywood et al., 2011a), with higher than modern surface temperatures and with boundary conditions and forcings similar to today (e.g., Pagani et al., 2009; Seki

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et al., 2010; Dowsett et al., 2012). Hence, the mid-Pliocene (hereafter Pliocene) is a particularly suitable period to test the sensitivity of the ice sheet in an environment relevant to future global change.

Multiple terrestrial and marine records for the Pliocene exist in the vicinity of Greenland and act as recorders of environmental change for the warmest interglacials during the Pliocene (Haywood et al., 2011a). Faunal and floral studies using microfossils, ostracoda, foraminifera, and palynological data around North and North Eastern Greenland (Kap København, Bennike and Böcher, 1990; Brouwers et al., 1991; Funder et al., 2001) and on East Greenland (Ille de France, Bennike and Weidick, 2001) indicate the presence of evergreen taiga/montane forest during the Pliocene. For parts of Southern Greenland, biogenic remains of coniferous trees (Willerslev et al., 2007) and independent reconstructions based on pollen records from marine sediments (de Vernal and Hillaire-Marcel, 2008) suggest boreal coniferous forest existed prior to the formation of a permanent ice sheet in central Greenland. Other marine cores from the Labrador Sea and Baffin Bay indicate cool mixed and cool conifer forest on Greenland (Willard, 1994; de Vernal and Mudie, 1989; de Vernal and Mudie, 1989). Adjacent land masses on Ellesmere and Baffin Islands, and reconstructions from the Canadian Archipelago, show a predominance of evergreen forest during Pliocene intervals (de Vernal and Mudie, 1989; Thompson and Fleming, 1996 and references therein, Ballantyne et al., 2006; Csank et al., 2011).

Ice-rafted-debris events recorded in nearby sediments in the North Atlantic are indicative of grounded ice on Greenland. Only a few episodic events occur in the early to mid-Pliocene, and become more abundant in the late Pliocene to early Pleistocene (Larsen et al., 1994; Wolf-Welling et al., 1996; Jansen et al., 2000; Kleiven et al., 2002; John and Krissek, 2002; Alley et al., 2010). This is consistent with sea surface temperatures and $\delta^{18}\text{O}$ reconstructions in the vicinity of Greenland, which suggest that highly variable and reduced Greenland ice cover prevailed in the late Pliocene before more stable and extensive ice sheets were attained in the early Pleistocene (Nielsen, 1991; Lawrence et al., 2009).

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These terrestrial and marine proxies indicate that there were substantial fluctuations in mid-Pliocene ice cover on Greenland, with intervals of little or no ice during the warmest Pliocene interglacials. However, there is considerable disagreement between sea-level high-stand reconstructions for the mid-Pliocene, with estimates from proxy records and isostatic modeling ranging from 5 m to 44 m above modern sea level (e.g., Raymo et al., 2011; Siddall et al., 2010 and references therein, Dowsett et al., 2010a). Stacks of benthic $\delta^{18}\text{O}$ (Lisiecki and Raymo, 2005; Miller et al., 2012) provide a global measure of cryospheric variability; however, it is challenging to disentangle Greenland and Antarctic ice-sheet fluctuations. Due to the light isotopic signature, in combination with the limited volume changes of the Greenland ice sheet the signal is hard to be inferred from the $\delta^{18}\text{O}$ global stack.

More detailed aspects such as the locations of individual ice centers on Pliocene Greenland require climate and ice-sheet modelling. A few modelling studies have attempted to simulate the Greenland Ice Sheet during the mid- to late Pliocene (Lunt et al., 2008, 2009; Hill, 2009; Dolan et al., 2011; Koenig et al., 2011; Solgaard et al., 2011; Koenig et al., 2014). However, assessment of these results has been hindered by the use of disparate initial and boundary conditions and prescribed external forcing.

Global datasets of proxy reconstructions for the mid-Pliocene have recently been established (PRISM3D, Dowsett et al., 2010a, b) providing an excellent framework for modelling studies. A consistent data-driven modelling approach can help to compare models and the sensitivity of ice sheets in the Pliocene leading to a better understanding of long-term future ice sheet response.

This paper aims to reconstruct the location and amount of grounded ice on mid-Pliocene Greenland by means of an ice sheet model intercomparison project (PLISMIP, Dolan et al., 2012). We apply a data-driven experimental design to provide a better understanding of the dynamics involved in Greenland's climatic and ice sheet variability. The specific objectives are to identify the uncertainties in sea level contribution due to ice sheet model differences, estimate the potential range in GrIS reconstructions of the mid-Pliocene warm interval, and to quantify the impact of prescribing different ice sheet

reconstructions in a climate model. A companion paper will follow, which, in combination with this study, will assess climate model dependency of ice sheet simulations over Greenland for the mid-Pliocene warm period (Dolan et al., 2014).

2 Methods

5 A set of forcing climatologies and initial conditions are applied to simulate Greenland's mass balance in the Pliocene relative to pre-industrial/modern. We first describe the experimental design, followed by model-specific details in Sect. 2.1.2.

2.1 Experimental design

10 Dolan et al. (2012) provides an overview of Pliocene Ice Sheet Modeling Intercomparison Project PLISMIP and describes its experimental design, but important details will be reiterated here for convenience. The Control Phase of this project aims at testing individual ice sheet model performances under present-day forcings, whereas the Pliocene Phase is designed to span an envelope of potential Pliocene scenarios by applying a range of climate forcings, and ice sheet model starting conditions on Greenland (Table 1, Fig. 1).

2.1.1 Forcing

15 In the first set of experiments (Control Phase), the ice sheet models (ISMs) are initialized with model-specific present-day ice sheets, and driven by climatologies either from a HadAM3 (Haywood et al., 2011b; Box, 2004) pre-industrial control run or from the independent NCEP/DOE AMIP-II re-analysis data set (hereafter NCEP2, Kanamitsu et al., 2002). These tests identify model-dependent biases when simulating present-day (or equivalent) Greenland ice sheets using a single GCM relevant for the inter-model interpretation of palaeo experiments.

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Two HadAM3 GCM climatologies are used to drive ISM simulations of Pliocene Greenland (Pliocene Phase, Fig. 1). The first climatology is from the main PlioMIP HadAM3 experiment using PRISM3 Pliocene boundary conditions (Dowsett et al., 2010a; Haywood et al., 2010; Box, 2004). The second climatology is from another HadAM3 GCM sensitivity experiment using the same PRISM3 boundary conditions except for isostatically adjusted ice-free Greenland topography. The latter scenario is added to quantify the uncertainties in simulating the maximum sea level contributions by imposing a significant ice mass in the Pliocene climatology used to force the ice sheet models. The initial Greenland Ice Sheet state for the ISM simulations is either that provided by Hill (2009) (see Dolan et al., 2011), or ISM-specific ice-free rebounded topographies.

There are various methods that account for temporal and spatial mismatches in scale between GCMs and ice sheet models (see Pollard, 2010 for an overview). Here, we avoid problems associated with the temporal mismatch by considering the equilibrated ice-sheet response to a given climate, rather than the transient behavior, i.e. Control and Pliocene GCM climatologies are used to drive individual ISMs to an equilibrated response. The spatial mismatch is accounted for as described below.

Monthly and annual mean temperatures and precipitation fields from the GCM and re-analysis dataset are re-gridded to the required ISM resolution using the interpolation method specific to each ISM (see Sect. 2.1.2 and references therein). To account for the high-resolution ISM orography compared to the coarser GCM and re-analysis grids, a uniform lapse rate correction is applied with a value of 8°C per km (Thompson and Pollard, 1997). First, the GCM/re-analysis topography and surface air temperatures are horizontally interpolated to the ISM grid, and then the temperature is corrected vertically to the ISM surface by $T - \gamma \cdot (Z_{\text{ISM}} - Z_{\text{GCM}})$, where T is the GCM/re-analysis surface air temperature, Z_{ISM} elevation of the ice sheet model, Z_{GCM} is the GCM/re-analysis surface elevation, and γ is the lapse rate. Each ISM simulation is run for 30 kyr, and extended to equilibrium if necessary in 10 kyr increments until the relative change in total ice volume per 1000 years falls below 0.01 %.

2.1.2 Ice sheet models

Table 3 provides an overview of ice sheet models applied in the experiments. The specifics of each ice sheet model that are relevant for the PLISMIP experiments, i.e. ISM resolution, mass balance calculation, geothermal heat flux, bedrock response model and further model details are available in the respective references (ANICE, de Boer et al., 2013; BASISM, Hill, 2009; Dolan et al., 2011; Glimmer, Rutt et al., 2009; GRISLI, Ritz and Rommelaere, 2001; Peyaud et al., 2007; IcIES, Saito, 2002; Saito and Abe-Ouchi, 2004; PSUI, Pollard and DeConto, 2007, 2012). Apart from Glimmer, all ISMs are run in absolute mode, i.e. forced with absolute climatologies, rather than using an anomaly method that combines climatological anomalies with a control climate (see e.g. Lunt et al., 2008).

3 Results

Initially we test the performance of ice sheet models in simulating present-day (or pre-industrial) ice sheets forced with GCM and re-analysis data, respectively (Sects. 3.1, 3.2). We analyze Pliocene scenarios both spatially and temporally (Sect. 3.3.1) before quantifying the variability (i) among ice sheet models and (ii) between climate scenarios through sets of statistical measures (Sect. 3.3.2).

3.1 Ice sheet model forcing

Absolute mean annual surface temperatures in modern control simulations from the HadAM3 GCM (Had_{ctrl}) are below freezing over all of Greenland with minimum values of -28°C centered over highest altitudes (Fig. 1). Precipitation follows the spatial pattern of temperature with relatively low values over much of Greenland except in regions of Southern Greenland where moisture transport from the North Atlantic increases precipitation to $> 1 \text{ m yr}^{-1}$. In comparison, annual surface temperatures and precipitation values from NCEP2 re-analysis ($\text{NCEP2}_{\text{ctrl}}$) are warmer by $5\text{--}7^{\circ}\text{C}$ and slightly wetter.

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For the Pliocene Phase, both driving climates ($\text{Had}_{\text{prism}}$, $\text{Had}_{\text{nogris}}$) show anomalies with respect to modern Pliocene temperatures with values from $+15^{\circ}\text{C}$ up to $+23^{\circ}\text{C}$ in regions where ice sheet reconstructions between Pliocene and modern deviate and elevation and ice-albedo feedbacks are maximized (see Dolan et al., 2012). An additional increase in surface temperatures of $+5\text{--}8^{\circ}\text{C}$ is simulated in response to ice-free conditions in the Pliocene GCM scenario $\text{Had}_{\text{nogris}}$ when compared to the Pliocene scenario $\text{Had}_{\text{prism}}$. Slightly higher elevations of the ice-free rebounded topography result in wetter ($0.6\text{--}1\text{ m yr}^{-1}$) and slightly colder surface temperatures ($\sim 1\text{--}2^{\circ}\text{C}$) in Southern Greenland.

3.2 Modern control Greenland Ice Sheet

Bamber et al. (2001a) use airborne laser altimeter data and cartographic data sets to reconstruct a digital elevation data set for Greenland. Ice thickness data is combined with the digital elevation model of Bamber et al. (2001b) resulting in an estimated volume of $2.931 \times 10^6\text{ km}^3$ for the present-day ice sheet. Calculations using Bamber et al. (2001b) data estimate the area to $1.67 \times 10^6\text{ km}^2$ (unpublished work, Byrd Polar Research Center). Equilibrated ice sheet model simulations using control GCM (Had_{ctrl}) and $\text{NCEP2}_{\text{ctrl}}$ forcings compare favorably with volumetric and areal estimates for modern GrIS (Table 2). Here we assume that ISMs forced with a pre-industrial simulation will reproduce an ice sheet configuration comparable to the present-day. The total of all ISMs averages to $3.46 \pm 0.43 \times 10^6\text{ km}^3$ for volume and to $2.03 \pm 0.19 \times 10^6\text{ km}^2$ for areal ice sheet extent, overestimating volume by 18 %, and area by 21 %. When forced with the HadAM3 climate, Glimmer produces an ice sheet which extends into the modern ocean in the Southeast, resulting in a large ice area. The GRISLI ISM significantly overestimates volume, which has consequences for the multi-model average (Table 2).

Figure 2 shows grid-cell elevation differences between simulated control scenarios ($\text{Control}_{\text{had}}$, $\text{Control}_{\text{ncep}}$) and modern-day observed ice sheets from Bamber et al. (2001a). Both control scenarios lead to comparable present-day ice volumes and ex-

tents relative to observations. In addition, modelled ice sheets forced by the GCM climatology Had_{ctrl} do not significantly differ from the ones forced by re-analysis data ($\text{NCEP2}_{\text{ctrl}}$). The majority of ISMs simulate present-day GrIS with overall lower elevations (< 250 m) in the center when compared to measurements (with the exception of GRISLI). Ice margins are generally overestimated accounting for the deviations in Table 2. Elevation changes in South West, East, and North East amount to > 1000 m at the ice margins, a feature uniformly seen in almost all ISMs.

3.3 Mid-Pliocene Greenland Ice Sheet

3.3.1 Evolution and equilibrated ice sheets

In Fig. 3 the temporal evolution of modelled ice volume is expressed as sea level equivalent meters for runs $\text{Plio}_{\text{prism.icefree}}$, $\text{Plio}_{\text{prism}}$, and $\text{Plio}_{\text{nogris.icefree}}$. Equilibrium is effectively reached for most of the runs and scenarios at year 30 k (see Sect. 2.1) although ISMs require a longer integration time to equilibrate to the $\text{Plio}_{\text{prism.icefree}}$ scenario due to larger deviations between forcing climatology and initial ice sheet model configuration on Greenland. Ice volumes for BASISM scenarios $\text{Plio}_{\text{prism.icefree}}$ and $\text{Plio}_{\text{prism}}$ and IcIES $\text{Plio}_{\text{prism.icefree}}$ do not come into equilibrium and remain oscillating between a stable maximum and minimum due to bedrock and ice interactions. In these instances, the median volume of a full cycle near the end of the run is selected as representative of ISM's end state. Except the reconstructions from GRISLI, all Pliocene scenarios lead to volumes that are below modern estimates. The range of modelled volumes from $\text{Plio}_{\text{prism.icefree}}$ and $\text{Plio}_{\text{prism}}$ are within sea level equivalent meters of 4.2–7.6 m and stand in contrast to the scenario $\text{Plio}_{\text{nogris.icefree}}$ with values between 0.8–1.7 m.

Although Pliocene simulations result in equilibrated ice sheets significantly smaller in comparison to modern, ice sheet location, extent and volumes differ considerably between Pliocene forcing scenarios (Fig. 4). Both Pliocene ice sheet scenarios forced with GCM forcing using PRISM3 boundary conditions ($\text{Had}_{\text{prism}}$) are more extensive than the scenario forced with $\text{Had}_{\text{nogris}}$. The latter forcing climatology has relatively higher

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surface temperatures over locations where ice reconstructions deviate (see Fig. 1). Forced with the same climatological means but different starting conditions, results from scenarios $\text{Plio}_{\text{prism}}$ and $\text{Plio}_{\text{prism.icefree}}$ deviate by only 9% in volume and 9% in extent. However, the average volume or area for the $\text{Plio}_{\text{nogris.icefree}}$ reconstructions correspond to a reduction of 19% and 36% relative to the latter two scenarios (see also Sect. 3.3.3).

3.3.2 Inter-model and inter-scenario analysis

Sample standard deviation (SSD) is a measure of the magnitude of a varying quantity. Here, it refers to the difference in the magnitude of simulated ice sheet thickness between the ice sheet models. SSD is calculated at each grid point by

$$\text{SSD} = \sqrt{\frac{x_1^2 + x_2^2 + \dots + x_n^2}{n - 1}} \quad (1)$$

where x_i is the difference between simulated ice sheet thickness in model (i) and the multi-model mean and n is the number of models. Where SSD is low, the difference in simulated thicknesses between the ISMs is small, and vice versa. It can be interpreted as the differences in the dynamics of the ice sheet models in these regions (Fig. 5a–c). SSD values are > 1500 m in Northeastern and Southcentral Greenland in both PRISM3D scenarios $\text{Plio}_{\text{prism}}$ and $\text{Plio}_{\text{prism.icefree}}$, whereas the ice sheet dome region on Eastern Greenland shows a low variability. Highest SSD values (> 2000) are calculated in Southern regions for the $\text{Plio}_{\text{nogris.icefree}}$ scenario. Other regions show generally low SSD values of < 800 m in variability.

When considered alongside the SSD plots, the ice sheet presence (Fig. 5d–f) suggests areas of Greenland that might be strongly affected by how each individual ISM calculates melting (cf. representation of ice dynamics). While higher values show regions where the majority of ISMs predict ice of any thickness, lower values indicate a reduced likelihood of ice presence for each particular scenario and correlates with

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regions of higher SSD values. The areal extent of the ice sheets is largely governed by how much melting is simulated in the ice sheet model and therefore inconsistencies in ice area may be ascribed to differences in the ISMs melt schemes. There are differences in the details of the predictions between the two experiments $\text{Plio}_{\text{prism.icefree}}$ and $\text{Plio}_{\text{prism}}$. Nevertheless, 100% of the models agree on the presence of large areas of ice over Central and Eastern Greenland, with 83% of the models predicting ice presence over areas in the South. In scenario $\text{Plio}_{\text{nogris.icefree}}$, ISMs agree on the existence of limited ice caps at Eastern and Southern high altitudes (100%) and deviate by 20–40% of how extensive the ice sheets are in those areas.

Figure 6 synthesizes the results from the model intercomparison. For Fig. 6a we define C as the confidence in reconstruction of ice presence at each grid point given a particular climatological forcing (inter-model confidence, where k_i is the number of models which have ice present in each scenario (i)). The total number of scenarios is defined by j and n is the total number of models (i.e. 6). Calculations are normalized to values 0–1. For Fig. 6a confidence is highest (1) when all models either agree on ice presence or absence in a particular grid square. Where half the models predict one result and the other half predict the opposite, confidence is low in the ice reconstruction ($C = 0$).

$$C = \frac{2}{j \cdot n} \sum_{i=1}^j \left| k_i - \frac{n}{2} \right| \quad (2)$$

High C (> 0.6 –1) is obtained for an extensive area of Greenland with highest values in Central and Eastern regions of Greenland. Lower inter-model confidence is obtained in areas in mid- to Southern Greenland with C between 0.25 and 0.6. In addition, we calculate the overall likelihood of ice presence in a grid square during the Pliocene given the scenarios we have tested. We calculate the sum of ice presence throughout all of the Pliocene ISM simulations (normalized to 0–1; Fig. 6b). In this case confidence is highest ($C = 1$) where all ISMs in each of the three Pliocene climate scenarios predict ice presence. We find the highest probability of ice presence in Eastern high altitude

regions in agreement with high confidence (C) simulated in those areas (see Fig. 6a). Ice is also reconstructed to be present in Southern Greenland, although shows slightly less agreement between ISMs.

3.3.3 Relative sea level contributions in the mid-Pliocene

5 Pliocene ice sheet simulations are analyzed relative to modern observed areal extent, volume and sea level equivalent height (Bamber et al., 2001a) in Fig. 7. In general, there is a correlation between relative changes in ice sheet volume and the equivalent change in areal extent. Relative changes of both Pliocene scenarios forced with GCM climatology ($\text{Had}_{\text{prism}}$) group and generally feature low within-group variability, 10 i.e. areally between $0.25\text{--}0.98 \times 10^6 \text{ km}^2$, and between $0.4\text{--}1.3 \times 10^6 \text{ km}^3$ in volume. Scenario $\text{Plio}_{\text{prism}}$ leads to slightly higher reductions in volume and area compared to $\text{Plio}_{\text{prism.nogris}}$. Significant losses are simulated for scenario $\text{Plio}_{\text{nogris.icefree}}$ relative to modern both areally and in terms of volume, corresponding to a sea level equivalent change of $\sim 6.1 \text{ m}$ with respect to Bamber et al. (2001b) and when considering all ISMs. 15 In summary, relative changes invoked by differing GCM forcings are significantly larger than inter-model changes for a particular scenario.

4 Discussion

We test ice sheet model performances under present-day conditions before intercomparing simulations from palaeo scenarios (Sect. 3.2). We find that there are no systematic biases introduced when using HadAM3 GCM climatology relative to control 20 experiments forced with NCEP2 re-analysis data. In general, ice sheet models compare favorably to observations, solely ice margins are overestimated and hence volume, a feature present in all ISMs. This can be attributed to problems in capturing the dynamic marginal ablation zones (see e.g. Hindmarsh, 1993; Ritz et al., 1996). In 25 turn, estimates of volume, extent and sea level stemming from observations may not

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be in equilibrium to the present climate, adding to the observed discrepancies between simulated ice sheets and present-day estimates (Fig. 1).

The three ice sheet model scenarios for the Pliocene Warm Period presented here are designed to assess the envelope of ice sheet presence on Greenland. Scenarios $\text{Plio}_{\text{prism}}$ and $\text{Plio}_{\text{prism.nogris}}$ lead to relatively extensive ice sheets due to a GCM forcing that mirrors prescribed ice sheets on Greenland (compare to original PRISM3 ice sheet reconstruction Haywood et al., 2010; Dowsett et al., 2010a). In turn, ISM results for scenario $\text{Plio}_{\text{nogris.icefree}}$ equilibrate to ice caps that are limited to the nucleation centers on high elevations in the East and South as a result of higher surface temperatures of an ice-free topography. Proxy records of terrestrial and oceanic origin (see Sect. 1) reconstruct a Pliocene Greenland similar to a projected future Greenland with very limited ice cover (see e.g. Ridley et al., 2005; Huybrechts et al., 2011). In particular, reconstructions of palaeo-vegetation for the Pliocene agree on ice-free conditions in North and North-East, and regions in Southern Greenland (e.g. Bennike and Weidick, 2001; Funder et al., 2001; Csank et al., 2011; Willerslev et al., 2007). We conclude that ice presence was most likely limited to Eastern and Southern high altitudes resembling scenario $\text{Plio}_{\text{nogris.icefree}}$, as simulated with highest confidence (Fig. 6), and in agreement with proxies.

Equilibrated ice sheet volumes and extents are a result and combination of initial ice sheet model configurations (boundary conditions), ice sheet default parameters and physical constants (Ritz et al., 1996; Rutt et al., 2009), and forcing climatologies. Model results show that Pliocene scenarios forced with the same GCM climatology are comparable, independent from the ice sheet model used. In turn, the Pliocene GCM forcing with altered boundary conditions on Greenland lead to significantly different, and relatively smaller ice sheets. Thus, starting ice sheet model configurations on Greenland are modeled to be of secondary importance in contrast to the uncertainties introduced by a change in the climate forcing. Although internal ISM-specific parameters have been shown to be critical in ice sheet simulations under similar forcing conditions (see Stone et al., 2010 for an overview), by using state-of the art ISMs available and run in

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their standard mode, our results point to less ice sheet model dependent results. The ISMs respond very similarly to a certain forcing over large areas of Greenland (see Sect. 3.3.2). As a result, alterations in the GCM boundary conditions have the potential to produce the greatest uncertainty in Pliocene ice sheet modeling.

The results presented here are of importance not just regarding ISM dependency, but they also provide a potential alternative to the PRISM3 ice sheet reconstructions when moving forward with PlioMIP Phase 2. Figure 7 displays ice sheet volumes derived from creating a multi-model mean (MMM) for each Pliocene scenario. It is possible that a MMM reconstruction across all the scenarios presented here would be more appropriate for future iterations of PlioMIP than simply relying on one ISM, however there will be difficulties in creating a spatially consistent MMM GrIS. Although the creation of a MMM may be fruitful, it is considered premature at present given the results presented here, which suggest that climatological forcing is more important than ISM dependency. It therefore follows that the climate model used to provide the climatological forcing could have a large impact on the simulated ice sheets. Dolan et al. (2014) is currently assessing the degree to which climate model dependency affects Pliocene ice sheet simulations and provides a useful companion to this paper.

5 Conclusions

PLISMIP was initiated in order to address the degree to which ice sheet reconstructions for the Pliocene are dependent on the choice of ISM (Dolan et al., 2012). We show that the degree of ISM dependency is relatively low and in fact the climatological forcing or the boundary conditions applied in the original climate model simulation are of higher importance in terms of the predicted Pliocene ice sheet. We also present the most likely locations of Pliocene ice on Greenland by means of intercomparing model results from six ISMs and forcing conditions. We find that less ice sheet model dependent results require forcings from various GCM scenarios with same the boundary conditions (Haywood et al., 2010, 2011b) to further constrain uncertainties in simu-

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lating ice on Pliocene Greenland. Moreover, given Greenland's sensitivity to imposed forcing we are in need of proxies on and in the proximity of Greenland to (i) help better constrain model starting conditions, and (ii) improve the validation of ice sheet model results.

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Table 1. Experiments for PLISMIP follow Control and Pliocene Phases. Forcing climatologies are from HadAM3 GCM control and NCEP re-analysis data (see Sect. 2.1). ISM simulations are initiated with modern, PRISM3 ice sheet configurations (Hill, 2009) and ice-free conditions with respective topographies. The ice-free scenarios use isostatically, rebounded topography on Greenland.

Run ID	Driving Climatology	ISM Configurations	Phase
Control _{had} Control _{ncep}	Had _{ctrl} NCEP2 _{ctrl}	Modern Modern	Control
Plio _{prism.icefree} Plio _{prism} Plio _{nogris.icefree}	Had _{prism} Had _{prism} Had _{plio.nogris}	Ice-free PRISM3 Ice-free	Pliocene

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**Table 2.** Equilibrated ice sheet volume [$\text{km}^3 \times 10^6$] and area [$\text{km}^2 \times 10^6$] for Control Phase scenario $\text{Control}_{\text{had}}$ for individual ice sheet models. ISMs_{all} denotes all-model means.

	Observations ^a	ANICE	BASISM	Glimmer	GRISLI	IcIES	PSUI	ISMs_{all}
Volume	2.93 ± 0.13	3.14	3.10	3.67	4.14	3.67	3.04	3.42 ± 0.47
Area	1.67 ± 0.05	2.08	1.66	2.22	2.01	2.15	2.07	2.04 ± 0.26

^a Volume and areal extent from Bamber et al. (2001a), standard deviation based on additional estimates by Ohmura (1991); Weng (1995); Ohmura et al. (1999); Bindoff et al. (2007); Lemke et al. (2007) and Bamber and Aspinall (2013).

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Table 3. Ice sheet model description table showing the resolution used in PLISMIP experiments, the mass balance method, whether there is basal sliding in the model and how the model uses the climatological forcing. All models apply the climatological forcing with absolute values of temperatures (T) and precipitation (PP), except Glimmer and are run on a resolution of 20 km \times 20 km. SIA = shallow ice approximation, SSA = shallow shelf approximation, PDD = positive degree-day scheme, finite difference = fd.

	Model Description	Mass Balance	Basal Sliding	Climate Forcing	References
ANICE	3-D thermo-dynamic, fd SIA explicit time-step	T and radiation	Yes	T and PP	de Boer et al. (2013)
BASISM	3-D thermo-mechanic, fd SIA semi-implicit	PDD	None	T and PP	Hindmarsh et al. (2001) Hill (2009)
Glimmer	3-D thermo-mechanic, fd SIA semi-implicit	PDD	None	T and PP	Rutt et al. (2009)
GRISLI	3-D thermo-mechanic Hybrid SIA/SSA semi-implicit	PDD	Yes	T and PP	Ritz and Rommelaere (2001) Peyaud et al. (2007)
IceS	3-D thermo-mechanic SIA semi-implicit	PDD	Yes	T and PP	Saito (2002) Saito and Abe-Ouchi (2004)
PSUI	3-D depth-averaged Hybrid SIA/SSA alternating implicit	PDD	Yes	T and PP	Pollard and DeConto (2007, 2012)

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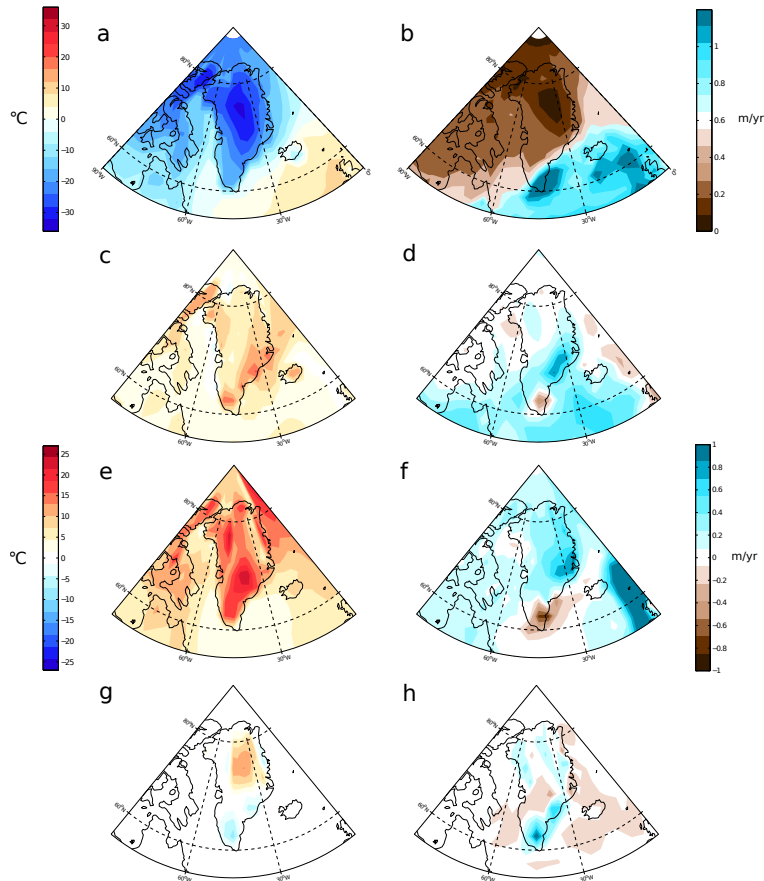


Figure 1. Control and Pliocene Phase driving climatologies. Annual surface temperatures [$^{\circ}\text{C}$] and precipitation [m yr^{-1}] for (a, b) Had_{ctrl} , (c, d) differences $\text{NCEP2}_{\text{ctrl}} - \text{Had}_{\text{ctrl}}$, (e, f) differences $\text{Had}_{\text{prism}} - \text{Had}_{\text{ctrl}}$, and (g, h) differences $\text{Had}_{\text{plio.nogris}} - \text{Had}_{\text{prism}}$. Note change in scales for absolute (a, b) and difference calculations (c-h).

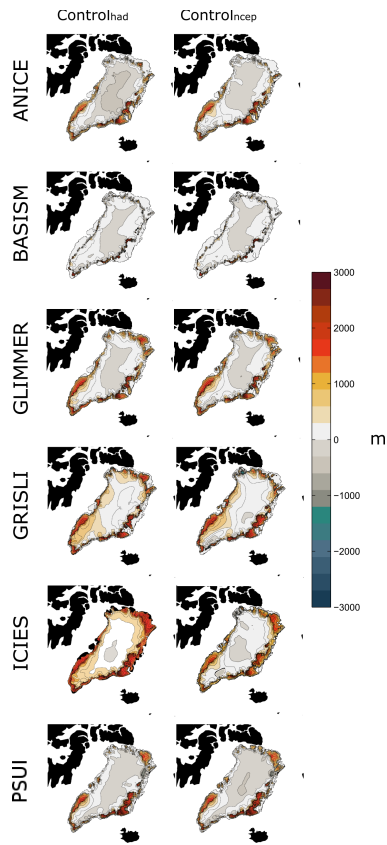


Figure 2. Ice sheet surface elevation [m] anomalies for Control_{had} (left panels) and Control_{ncep} (right panels) relative to observed present-day Greenland Ice Sheet calculations from Bamber et al. (2001a) for individual ice sheet models ANICE, BASISM, Glimmer, GRISLI, IclES and PSUI (from top to bottom). Modern-day coastlines are used and ocean is masked out for plotting the anomalies.

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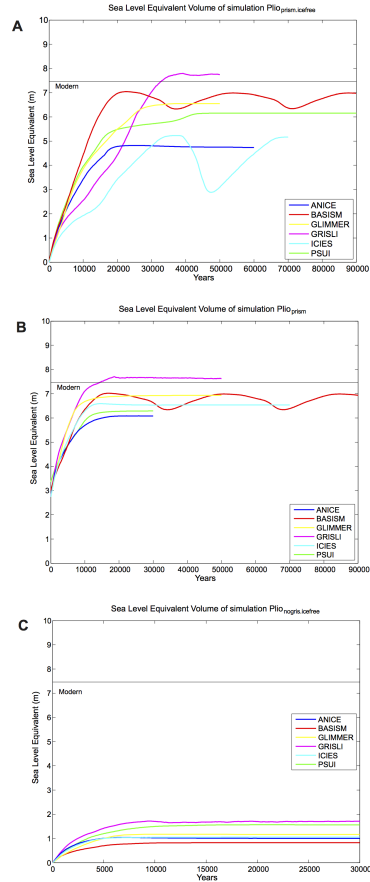


Figure 3. Evolution of ice sheet volumes expressed in sea level equivalent meters [m] for Pliocene scenarios **(a)** $Plio_{prim.icefree}$, **(b)** $Plio_{prim}$, and **(c)** $Plio_{nogris.icefree}$ for individual ice sheet models. Observed present-day values from Bamber et al. (2001a) are indicated for reference. Note changes in integration lengths for scenarios (x-axis).



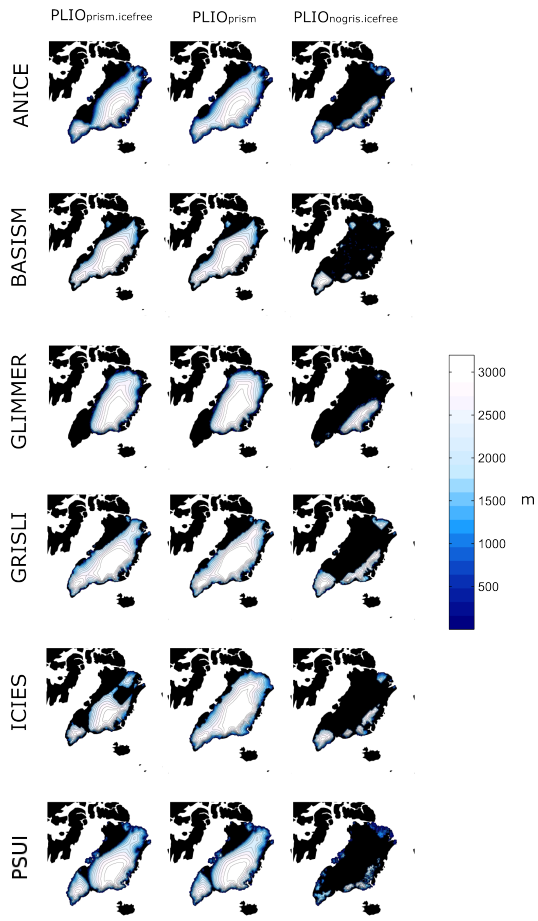


Figure 4. Ice sheet surface elevation [m] for Pliocene scenarios $PLIO_{prism.icefree}$ (left panels), $PLIO_{prism}$ (middle panels), and $PLIO_{nogris.icefree}$ (right panels) for individual ice sheet models ANICE, BASISM, Glimmer, GRISLI, ICIES and PSUI (from top to bottom).

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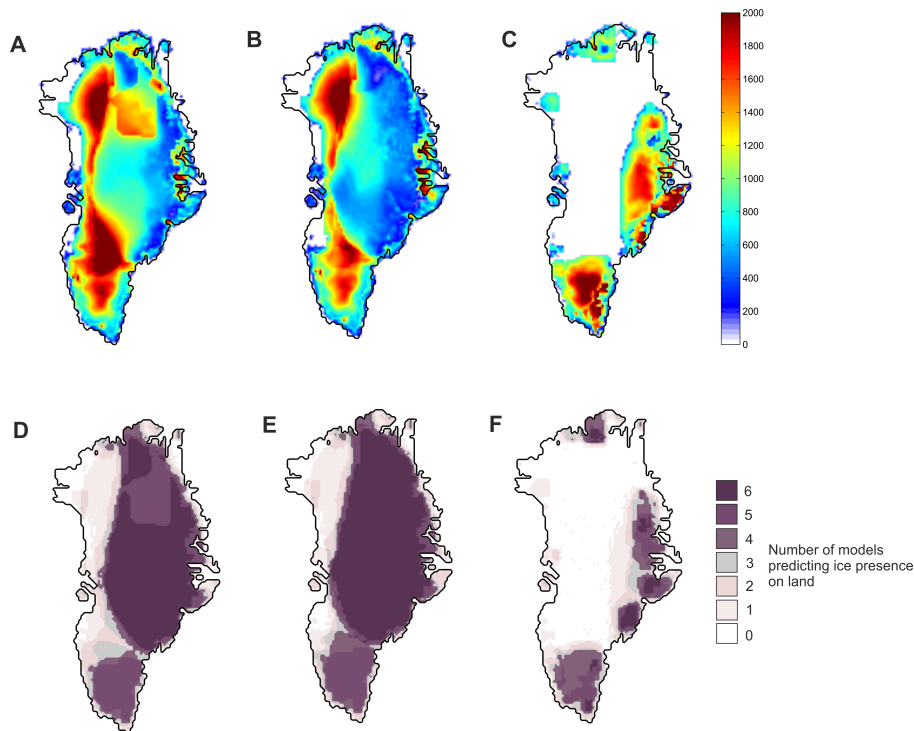


Figure 5. Measures of (a–c) sample standard deviation (SSD) and (d–f) ice sheet presence for scenarios Plio_{prism.icefree} (left panels), Plio_{prism} (middle panels), and Plio_{nogris.icefree} (right panels). See text for calculations.

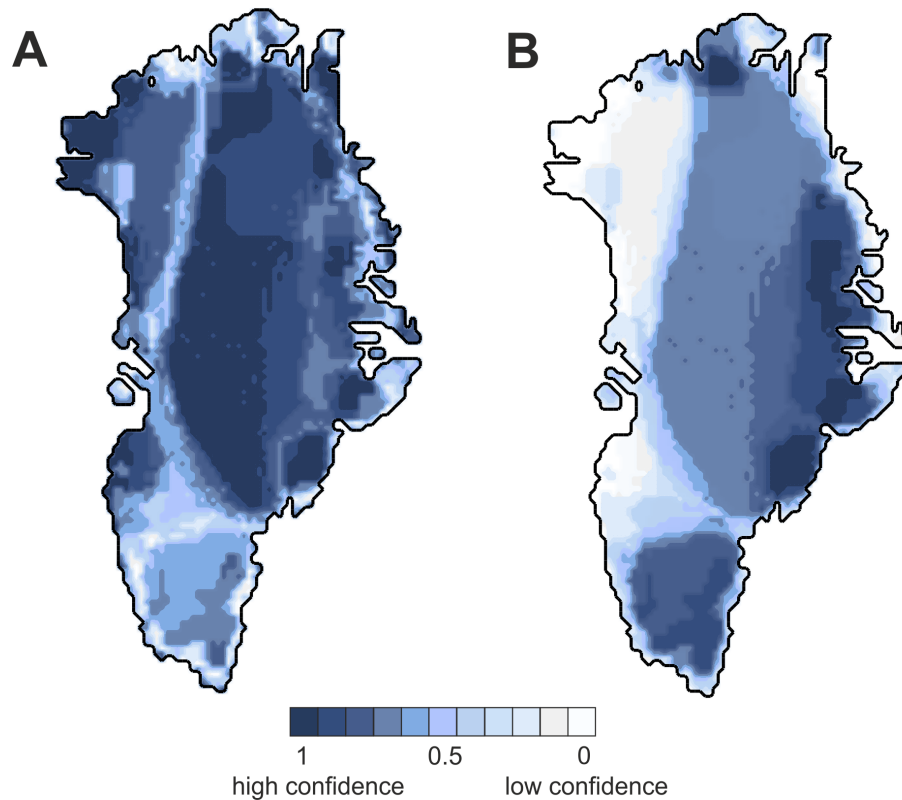


Figure 6. Measures of (a) inter-model and (b) overall confidence in Pliocene ice sheet simulations normalized to 0–1. See text for calculations.

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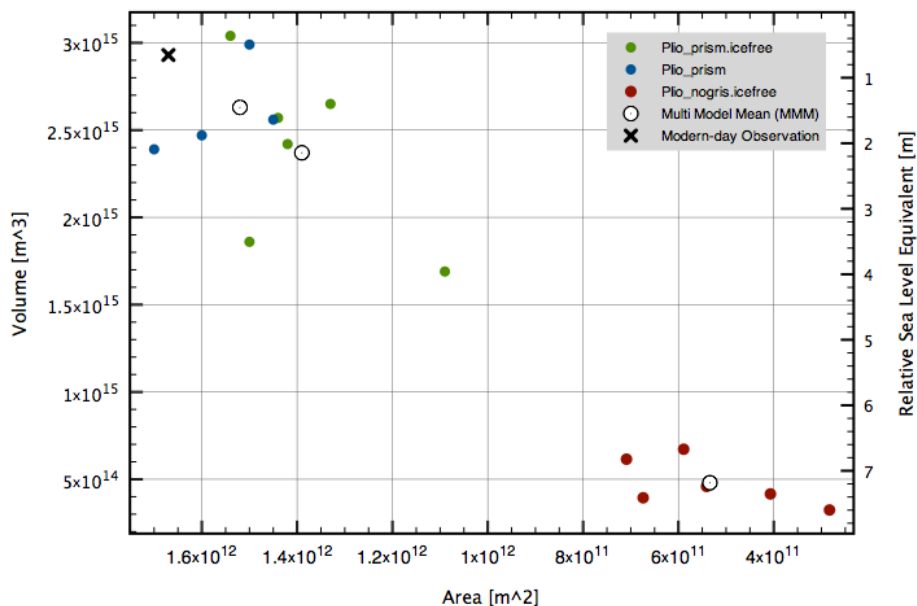


Figure 7. Ice sheet volume [m³] and area [m²] of Pliocene scenarios Plio_{prism.icefree} (green), Plio_{prism} (blue), and Plio_{nogris.icefree} (red) with relative sea level equivalent [m] with respect to present day reconstructions. Cross denotes volume and area for Bamber et al. (2001a), open circles indicate multi model means (MMM) for the respective scenarios.

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