<u>Response to reviewers for paper: Using results from the PlioMIP ensemble to investigate the Greenland Ice Sheet during the warm Pliocene</u>

We thank the reviewer for their helpful review of the paper. We have addressed their comments as outlined below.

Reviewer 1 (Bas de Boer)

The manuscript by Dolan et al, describes a thorough examination of the influence of the modelled climate over Greenland on the Greenland ice sheet during the warm Pliocene. The manuscript is a follow-up of the PLISMIP paper by Koenig et al. (CPD, 2014b), but here one ice-sheet model (the model BASISM) is used with 15 different realisations of the Pliocene climate performed in the PlioMIP ensemble. I think the paper is well written and the analyses performed are thorough and complete. This manuscript describes a good addition to the ice-sheet modelling work performed on the Pliocene and is of a good quality. The manuscript is well structured and the analysis performed on the ice-sheet model and the climate models (e.g. the discussion of the albedo) is clear. I accept this manuscript with minor revisions. Most comments given below are minor and are on rewording of the text. I have one major point, and that is the low influence of the different parameter values on the pre-industrial simulations (Fig. 5). As given in Table 2, the parameter space is quite sufficient to get a nice spread for the Pliocene (Fig. 7), but it is striking to me that this does not occur for the pre-industrial. I think a lower sensitivity could be expected, but no differences at all, whereas mean climatology (Table 3) is quite diverse between models, is something that needs some additional investigation of model output.

Specific comments

Page 3485

Line 2: In recent literature this time period from 3.264 to 3.025 Myr ago does no longer apply to the mid-Pliocene but rather to the mid-Piacenzian (e.g. Dowsett et al., Scientific Reports, 2013) or the Late Pliocene. This should be changed throughout the text.

To retain consistency with the original PlioMIP naming conventions, we would prefer not to use mid-Piacenzian or Late Pliocene as this may be confusing. However, we will describe the rationale behind the naming conventions that we use here.

7: warmer-than-modern could be changed to warmer than present-day climate.

Done

12-14: Mention here that you have used 15 models from PlioMIP.

Done

18: the surface albedo

Done

21: Be more specific, mention which data.

Data pertaining to ice extent - done

25: Replace these two references with the IPCC AR5 chapters.

References replaced with Church et al. (2013), Masson-Delmotte et al. (2013) and Vaughan et al. (2013)

Page 3486

13: You could also refer here to Rovere (EPSL, 2014).

Done

14-18: Mainly due to insolation changed (for the previous interglacial, the Eemian). One could also refer here to Van de Berg et al. (Nat Geo, 2011) on the importance of insolation on melting of ice on Greenland.

Done

Page 3487

8: Why not refer to Koenig, 2014b here?

Done

11: Replace ‘and’ before GENESIS with a comma.

Done

18: Replace ‘ice sheet model’ with ISM (this should be replaced a number of times in the text).

Done in all cases

29: Here, it is first mentioned that 15 different models are used, this could also be mentioned in the Abstract.

Done

Page 3488

15-16: Acronym of PlioMIP is already mention in page 3486, change sentence to: “..mPWP, PLIOMIP (Haywood et al., 2010, 2011) was initiated ..”.

Done

Line 23 and line 1 on page 3489: Throughout the text you refer to the AGCM as ‘Experiment 1’ and the AOGCM as ‘Experiment 2’. I understand that this originates from the PlioMIP paper as described in Haywood et al. (2010, 2011a). But in this manuscript it is a bit confusing since you do not run the climate-model experiments but use the output to force one ice-sheet model. I think in this manuscript it is sufficient to just mention the two separate experiments shortly in this section (2.1) and then in the remainder of the text state either AGCMs or AOGCMs and not use Experiment 1 or 2.

Done in all cases

Page 3490

8: Acronym of BASISM already given on page 3487, just state BASISM, without brackets.

Done

19-20: What do you mean with 'following Hill (2009)'? Do you use the same methods as described in that study? Please explain and rephrase sentence.

Done

Page 3491

23: Remove 'atmospheric'.

Done

Page 3492

27: ".. for each model simulation."

Done

Page 3493

1: Change to: ".. each simulation reconstructs the observations of ice thickness.".

Done

1-2: Add 'the' before 'normalised'.

Done

2: Explain here what you mean with the normalised RSME.

The measure we have used is actually simply RMSE – normalised has been removed and the text altered to: "RMSE describes the magnitude of the differences between two fields (e.g. observed ice thickness and simulated ice thickness). In both cases, lower values describe a better match between the modelled and the observed GrIS."

19-25: In the discussion of the precipitation of the models, rather start with discussing all GCMs instead of only mentioning MRI.

Sentences have been rearranged accordingly

Page 3494

5-9: It is surprising to me that there is so little difference between all the experiments. I think this should be checked since the parameters in Table 2 are quite different and the Pliocene experiments do show this strong variability.

In this ISM framework, there is a low sensitivity of the pre-industrial GrIS to parameter choices concerning mass balance. We interpret this to be a function of the fact that the modern ablation zone is constrained to the steep slopes on the periphery of the ice sheet. While we fix the grounding line at the modern extent (as our model does not explicitly simulate ice calving at the margins), so ice does not expand out to the ocean, we also have a build-up of ice in the central regions of the GrIS. Therefore, there are little differences between each of the ensemble members as no combination of parameters causes significant melting of the pre-industrial GrIS. Whilst, there is discussion as to the inclusion of a precipitation correction to reduce our bias towards large ice sheets (see text inserted based on comments of reviewer 2), this has not been included as any correction remains uncertain in palaeoclimates. It should also be noted that BASISM performs on par with other SIA ISMs under similar pre-industrial conditions (see Koenig et al., 2014b).

Page 3495

7-9: Replace ‘No’ with Not’, rephrase sentence, perhaps last part first.

Done

10-13: There are 2 metrics involved here, so also mention the difference in volume.

Done – differences in the volumes of the simulated pre-industrial GrISs has also been included.

14: Missing Ritz, 1997 in reference list.

Done

19: Change to: (Fig. 1 in Dowsett et al., 2010).

The reference to Figure 1 in the manuscript is correct

23: Please read the statement in Robinson et al., (2011): page 393, right column the second to last paragraph of the Conclusions (starting with “None of ..”), i.e. a realistic modern realisation does not necessarily mean a realistic Pliocene simulation.. A short discussion similar like this would be appropriate here.

We have added a short discussion on this into the manuscript where we discuss the limitations of this approach to allowing us to define the most likely Pliocene GrIS.

“A final caveat to this research is derived from the uncertainty as to whether a good simulation of the modern GrIS (when compared to observations) necessarily implies a realistic representation of the Pliocene GrIS. Robinson et al. (2011) found that when simulating the Eemian GrIS (where significantly more constraints are available than for the Pliocene), the ISM simulation that gave the most realistic modern ice sheet, gave an entirely unrealistic ice sheet for the Eemian when compared with data. This highlights the need for further palaeodata constraints regarding the extent and thickness (where possible) of the Pliocene GrIS in order to thoroughly assess the results presented here.”

Page 3496

10-11: Refer here to Fig. 7 (the red dots) as the model simulations that are used for these maps, as is also done in the caption of Fig. 9.

Done

Page 3498

6: Change 'balance of energy' to 'energy balance'.

Done

6: Why mention global heat, rather point out how it changes over Greenland.

The studies that we are referring to here only consider how the global balance of energy changes under past conditions. Later we go on to discuss how the energy balance might be altered over Greenland.

Page 3499

23: What do you mean with 'differing degrees', please rephrase.

The study by Koenig et al. (2014b) suggests that the Greenland ice sheet is very sensitive to changes in SSTs prescribed in a climate model and that this response is mainly due to temperature changes over the ice sheet. Conversely, Hill et al. (2010) suggest that the ice sheet response is minimal and where it does occur, is dominated by changes in precipitation. The phrase 'differing degrees' has been elaborated upon, but it is also noted that this studies are not directly comparable as they use different modelling frameworks and different initial conditions.

22-26: Too long sentence, please rephrase to two sentences.

Done

Page 3500

7-11: Looking at Figures 10,11 and 12 it seems to me the largest differences occur for the MRI models (both the AGCM and the AOGCM). This should be mentioned/discussed here as well.

We have refrained from a thorough discussion of the MRI ensemble member here, as understanding the differences in this climate model is beyond the scope of this paper. However, we have mentioned that MRI is an outlier in the PlioMIP ensemble in terms of its representation of clear sky albedo.

9-11: Rephrase to: "Whereas using CCSM4, which . . . summer, produces one of the largest predicted ice sheets".

Done

Sections 4.2 and 4.3: Nicely written

Page 3504

19-21: There is no recent publication that could be used instead of 'personal communication'?

No, this work was originally published in 1989 and the reassessment of the work by Anne de Vernal was presented at a conference in 2014 but is yet to be published.

26-27: An additional note could be added here on which kind of data, with appropriate references.

A brief note regarding which kind of data has been added: “Clearly however, there is a critical need for further data pertaining to ice extent (e.g. Bierman et al., 2014) or potentially the Greenland climate (such as vegetation records) in order to more accurately constrain this reconstruction.”

References

Page 3506; line 24: Capitalize: PA4213

Done

Page 3515: Add Ritz, 1997

Done

Tables

Table 2: Just wondering why you have chosen for the PDD factor of ice from 5,6,8 and 14 and not a linear rate (like the other two parameters) like 5,8,11 and 14? Please clarify your choice of parameter space.

The reviewer is correct that the PDD factor of snow and the lapse rate have been sampled at a linear rate, however the PDD factor of ice has not. We wanted to sample an appropriate range of PDD factors for ice, so we used the end members referenced in most studies (e.g. 5 and 14 mm day^{-1} – although the study of Lunt et al. (2008a) used an unrealistically high value for ice 64 mm day^{-1}. We also wanted to use PDD factors which most frequently were cited in the literature and also used previously within BASISM (e.g. 6 and 8 mm day^{-1}). We do not anticipate that our sampling strategy will affect the overall conclusions based on the results presented in this paper.

Table 3: Explain in the caption the exact region used for these numbers, all land area or only all ice-covered area? Perhaps change the unit of mean annual precipitation to mm per year? (a bit easier to grasp for a meteorologist at least..).

In the original submission we had defined the Greenland area using the region between 25°W to 60°W and 57°N to 85°N. However, as this also incorporates area of ocean, we have now amended our values to be representative of the land area only. The Greenland land area is defined by the land-sea mask given to each of the climate models. All numbers in Table 3 have been amended accordingly and text which refers to the absolute values has been changed. The unit of mean annual precipitation has not been changed as in its current state (mm per year) it allows for easy comparison between the precipitation values over Greenland shown in Figure 3 and the global precipitation values presented in Haywood et al. (2013) and other PlioMIP summary papers.

Table 4: State in the caption that these are differences, and between what and what? Differences in the Maximum ice thickness (in km?) seem a bit odd to me, and are these actually used in the text? Please explain.

The differences have been explained in the table caption and the maximum ice thickness differences have been removed entirely as they are not referred to in the text.

Figures

Figure 5: Perhaps check SMB In the same way? If I look at the precipitation and temperature in Table 3 and Figures 2, 3 and 4 this should be quite different. . .

The SMB shown in Figure 5 is correct and depicts the areas of ablation and accumulation calculated at the first model time-step (before a lapse rate correction has been applied).

Figure 5 and 7: Could you show the modern and PRISM3 volumes in these figures by e.g. a horizontal dashed line?

Done

Figure 12: Replace Experiment 1 and 2 (Exp1, Exp2) with AGCM and AOGCM, respectively.

Done

Reviewer 2 (Anonymous)

General comments

The manuscript of Dolan et al. investigates the sensitivity of the Greenland Ice Sheet (GrIS) to atmospheric forcing fields during the warm Pliocene. The document is nicely written and presents some really interesting analysis. This paper is a certainly a valuable contribution, and in particular it represents a needed step towards the next phase of PlioMIP. However, the manuscript could be improved in some places. The ISM description is generally too weak. I can understand that the ISM physical description is not necessarily needed for this paper, but I would have appreciated more description of the SMB computation. In particular, the chosen SMB model is very simple and a justification for this choice is needed. For example, some possible improvements of the original PDD scheme are not even considered nor listed, such as melt factors depending on temperature (Tarasov and Peltier, 2002) or water retention (Janssens and Huybrechts, 2000). Also, from the text, I assume you used mean annual and July temperature in order to evaluate the PDD, via a sinus function. This seems again a strong simplification and, therefore, a justification for not using directly the monthly fields from the climate models would be appreciated. Also, there is no information about an eventual partitioning between snow and rain from the total precipitation. In addition, the authors discard the precipitation correction for elevation changes. I acknowledge the fact that a simple parametrisation is far from obvious, as precipitation is a complex process that cannot be represented by a function of altitude only. However, neglecting this effect strikes me as a strong assumption. This could be justify for small changes in the ice sheet topography (such as for the initial downscaling for example).

However, for large changes happening during the Pliocene (from present day ice sheet to almost ice free), this assumption may be inappropriate. Considering their initial SMB (Fig. 8), I believe that COSMOS, MIROC or MRI (AGCM) would have presented much reduced GrIS with a precipitation correction factor, as we cannot really expect that with a 3km gain on the west flank on the ice sheet (and thus a cooling of ~18◦C) the precipitation would stay the same. Neglecting the precipitation correction would probably tend to exacerbate model differences and it does not seem justified. At least a discussion would be greatly appreciated.

We thank the reviewer for their general comments and are happy to provide more detail and discussion as suggested. We have added a section further describing the conversion of temperatures to the PDD scheme and detailing why July temperatures are used rather than all the monthly temperatures. We have also added a section describing the non-linear nature of precipitation and how this impacts the use of parameterizations on Greenland. Finally we have added the suggested references for improved PDD parameterizations, along with some justification for not using them.

Specific comments

3483 Title Maybe switch from Pliocene to mid-Pliocene warm period?

Done

3485-3488 Introduction It would be great to have a little bit more of a discussion about the data here. Some references you cited later (e.g. Bierman et al. (2014) about summit being ice free or de Vernal suggesting a forested South Greenland) do not appear in this section. Also, how well the models capture the Arctic warming as reconstructed from proxy?

Added suggested references and also some giving general picture of high-latitude warming in data and model of the Pliocene.

3488 It would have made more sense to me to see the inter-model differences (currently in 3.1.) in here, instead of in the results section.

Moved paragraph describing PlioMIP Greenland climatologies

3490 l. 18-19 Again, it seems that you don't use the monthly fields from the climate models. What about the seasonality of climate fields in the PlioMIP ensemble? Could this seasonality have an impact on the computed PDD? Is July temperature meant to represent mean summer temperature?

As stated above, we have now given more information regarding the computation of PDDs in BASISM.

3490 l.26 is this lapse rate used to correct the temperature as the elevation change during the simulation?

Added clarification of lapse rate used "both in the initial conditions and as the ice sheet surface evolves during the simulation".

3491 l.26-3492 l.10 Following my main comment, Charbit et al. (2013) suggest that PDD scheme flavours strongly impact the model results for glacial inception, not only the ablation parameter values. Also, you may want to add a bit of discussion regarding the results of Rogozhina and Rau (2014) on the importance of the temperature standard deviation?

Our model uses an empirically based relationship between temperature and PDDs, in order to minimise uncertainties due to parameterisations tuned to modern day climatologies, so most of the discussion in these papers is not applicable. We have included more discussion of the melt scheme used, see above.

3492 l.4 I think you meant “2008a”.

Changed

3492 l.21-22 And for the Pliocene run?

Added a sentence making clear that “These parameter sets were than used with each of the climate forcings from the PlioMIP ensemble.”

3494 l.3-14 I might be wrong but I think the low sensitivity of the pre-industrial ice sheet to ablation rates comes from the fact that you have very little ablation over the GrIS under pre-industrial climate. Especially if as you have a bias towards a higher ice sheet, the lapse rate would tend to limit further the melt. A time series of melt for the pre-industrial simulation might help you to diagnose this? Again, maybe part of this low sensitivity is related to the fact that you discard the precipitation correction?

Added some further explanatory text to the discussion of pre-industrial ice sheet simulations.

3494 l.25-28 True, and the horizontal model resolution is also crucial.

Added note about resolution

3495 l.3-6 If you start your simulation with a present-day geometry, you will eventually end up with an inner sea. You need to describe your initial ice configuration (bedrock, ice thickness, ice temperature) for the Pliocene experiments.

Added a couple of sentences describing the isostatic rebound model used in section 2.2.

3498 l.9 Annual / summer mean?

Added “annual mean”

3498 l.10 “A strong warming” compared to what? When?

Rephrased to make this sentence clearer

3498 l.24-25 I suggest you get rid of “amin” notation.

Removed notation

3500 I think it could be useful to have a summarizing table with some averaged numbers for each ensemble member (GrIS volume difference during the mPWP, temperature, precipitation, SST, ice fraction).

We already have two tables which we believe summarises this information. Table 3 gives the precipitation and temperature values (for the Pliocene and pre-industrial) and Table 4 shows the GrIS volume and area for each ensemble member.

3504 l.13-18 The findings of Bierman et al. (2014) are that soils have been subaerially exposed for more than 1 million years. Is it not jumping onto conclusion to claim that it was ice free during the warm Pliocene?

We agree, but the paper suggested that this could be the case. We have rephrased it to be clear that the implications are from the source.

3518 Table 1 What is preferred or alternate LSM?

Added reference and more information on the land-sea mask configuration

3519 Table 2 I suggest you add in a separate table, the values corresponding to the red-blue-yellow filled dot?

Table has been added to the supplementary information for the paper

3520 Table 3 What is the “Greenland region”? Formatting: COSMOS-AOGCM row.

Calculations for climate fields over Greenland have been changed – see response to Reviewer 1 regarding Table 3

3523 Figure 1 Is there any isostatic model embedded in BASISM? Also, where the bedrock data comes from, surely there is some kind of isostatic adjustment in Figure 1. Stone et al. (2010) suggested that the bedrock was a major source of model sensitivity and you may want to comment a little bit about that? Again, you should specify somewhere the initial ice configuration for the Pliocene simulations.

Section has been added to ISM description based on previous comments

3524 Figure 2 The differences are on the same height level? If this is surface level, I don’t understand why we cannot see the impact of the topography difference on some of the models.

The differences shown are from the original model simulations and have not been corrected to one height. As we have used the field surface air temperature, we have added “surface air” to figure caption to make this clearer.

3526 Figure 4 Same as before.

Added “surface air” to figure caption

3532-3 Figure 10-11 Annual mean?

Added “annual mean” to figure caption

~~Using results from the PlioMIP ensemble to investigate the Greenland Ice Sheet during the warm Pliocene warm periodc~~

by

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Abstract

During the mid-Pliocene Warm Period (3.264 to 3.025 million years ago), global mean temperature was similar to that predicted for the end of this century, and atmospheric carbon dioxide concentrations were higher than pre-industrial levels. Sea level was also higher than today, implying a significant reduction in the extent of the ice sheets. Thus, the mid-Pliocene Warm Period provides a natural laboratory in which to investigate the long-term response of the Earth's ice sheets and sea level in a warmer-than-~~modern~~ present-day world.

At present, our understanding of the Greenland ice sheet during the warmest intervals of the mid-Pliocene is generally based upon predictions using single climate and ice sheet models. Therefore, it is essential that the model dependency of these results is assessed. The Pliocene Model Intercomparison Project (PlioMIP) has brought together nine international modelling groups to simulate the warm climate of the Pliocene. Here we use the climatological fields derived from the results of the 15 PlioMIP climate models to force an offline ice sheet model.

We show that Pliocene ice sheet reconstructions are highly dependent upon the forcing climatology used, with Greenland reconstructions ranging from an ice-free state to a near modern ice sheet. An analysis of the surface albedo ~~differences~~ variability between the climate models over Greenland offers insights into the drivers of inter-model differences. As we demonstrate that the climate model dependency of our results is high, we highlight the necessity of data-based constraints of ice extent in developing our understanding of the Pliocene Greenland ice sheet.

1. Introduction

The response of the Earth's ice sheets to a warming climate is a critical uncertainty in future predictions of climate and sea level (Church et al., 2013; Masson-Delmotte et al., 2013; Vaughan et al., 2013~~Lemke et al., 2007; Meehl et al., 2007~~). Therefore, there is increasing interest in understanding the nature and behaviour of the major ice sheets during warm intervals in Earth history. The Pliocene Epoch, and more specifically warm 'interglacial' events within the mid-Pliocene, is a particularly well documented pre-Quaternary environment which has become the focus for intense study within the Pliocene Model Intercomparison Project (PlioMIP; Haywood et al., 2010; 2011a). The mid-Pliocene warm period (mPWP; 3.26 to 3.025 million years ago; Dowsett et al., 2010) is predicted to have been between 2°C and 3°C warmer than pre-industrial (Haywood et al., 2009; 2013; Lunt et al., 2010) and estimates of atmospheric carbon dioxide (CO_2) concentrations suggest levels of up to 450 *ppmv* (Pagani et al., 2010; Seki et al., 2010). Although recent literature the terms mid-Piacenzian or Late Pliocene warm events have been used, here we retain consistency with the original PlioMIP naming convention and use the mPWP. The IPCC 5th Assessment Report states with high confidence that global mean sea level was above present (up to 20 m) during warm intervals of the mid-Pliocene (Masson-Delmotte et al., 2013) and individual records of sea level high-stands (~20 m) support the reduction in the extent of the ice sheets at this time (e.g. Miller et al., 2012; Rovere et al., 2014; Rohling et al., 2014).

Proxy records of palaeotemperature derived from ice cores (Dahl-Jensen et al., 1998; Cuffey and Marshall, 2000; Johnsen et al., 2001; Rasmussen et al., 2006) and numerical modelling (Otto-Bliesner et al., 2006; Overpeck et al., 2006; van de Berg et al., 2011; Born et al., 2012; Quiquet et al., 2013; Stone et al., 2013) of more recent interglacials demonstrate that the Greenland ice sheet (GrIS) has a large sensitivity to high-latitude warming. However, there is little proximal evidence to indicate the volume or extent of the GrIS during the warmest intervals of the mid-Pliocene. Evidence of long lasting subaerial soil formation at the base of the central Greenland Ice Sheet have been suggested as evidence for persistent reduction in Pliocene ice, but the soils have not been positively dated as relating to this period (Bierman et al., 2014). The presence of forest fragments in the Kap København Formation in the far North of Greenland up until 2.4 Ma (Funder et al., 2001) suggests that this area may have been ice-free through intervals of the mid-Pliocene. Fragments of evergreen taiga forest in Pliocene sediments at Ile de France (Bennike et al., 2002) also suggest that ice marginal regions were much warmer during the Pliocene. Records from the central Labrador Sea suggest that landmasses adjacent to Greenland, such as Ellesmere and Baffin Island, show a predominance of evergreen forest during intervals of the Pliocene (De Vernal and Mudie, 1989; Thompson and Flemming, 1996; Ballantyne et al., 2006; Csank et al., 2011). Additionally, temperature estimates from peat deposits in the Canadian High Arctic (Beaver Pond) suggest elevated Pliocene Arctic temperatures (Ballantyne et al., 2010). Although there are no Pliocene temperature records from Greenland against which to test the climate model simulations, there is generally a cool bias in the models compared to the available data in the Northern high latitudes (Dowsett et al., 2012; Salzmann et al., 2013).

While useful, proxy evidence is too sparse and uncertain to enable a detailed reconstruction of the extent and location of mid-Pliocene ice sheets. Therefore, a variety of modelling frameworks have been adopted in order to simulate the mass balance of the GrIS and reconstruct potential ice sheet configurations during the mid-Pliocene (Lunt et al., 2008; 2009; Hill, 2009; Hill et al., 2010; Dolan et al., 2011; Koenig et al., 2011; 2014a; 2014b). These modelling frameworks have generally included the offline coupling of an ice sheet model (ISM) to a climate model, and have been limited to the use of three climate models; the UKMO UM (UK Met Office Unified Model; e.g. Hill et al., 2010; Dolan et al., 2011)~~ and~~, GENESIS (e.g. Koenig et al., 2011) and multiple versions of CAM (Community Atmosphere Model; e.g. Yan et al., 2014). Although all available simulations suggest that the GrIS was reduced in size during the mid-Pliocene warm period, the model dependency of the results is yet to be robustly assessed. The extent to which ice sheet reconstructions are dependent on the ISM employed is addressed through a sub-project of PlioMIP, entitled the Pliocene Ice Sheet Modelling Intercomparison Project (PLISMIP; Dolan et al., 2012). Results from Koenig et al. (2014b) suggest that ~~ice sheet model~~ISM dependency is low. Here, we will address the question of climate model dependency utilising climate model outputs from PlioMIP (Chan et al., 2011; Bragg et al., 2012; Contoux et al., 2012; Stepanek and Lohmann, 2012; Yan et al., 2012; Kamae and Ueda, 2012; Zhang and Yan, 2012; Zhang et al., 2012; Chandler et al. 2013; Rosenbloom et al., 2013) to force the British Antarctic Survey ISM (BASISM). Results from PlioMIP present a unique opportunity to sample differences in model predictions of climate and how this impacts on our reconstruction of the GrIS.

Initially a summary of the PlioMIP experimental design will be provided, followed by a description of the offline coupling method adopted for the ISM simulations in this study, which will include details of the climate differences over Greenland as derived from the PlioMIP ensemble. A discussion of the differences between equilibrium-state ice sheet simulations using the climatological forcing from the fifteen different climate model experiments in the PlioMIP ensemble will follow and we will conclude with an assessment of the potential causes of any discrepancies and suggestions for future modelling strategies of the mPWP GrIS.

The aims of this paper can be summarised as:

- To assess the extent to which GrIS reconstructions for the mPWP are dependent upon the climate model used to force the ~~ice sheet model~~ISM.
- To understand the potential reasons for any differences between the simulated GrISs~~climate models~~ by considering factors which may affect the climate representation over Greenland in the PlioMIP models.
- To inform decisions regarding the prescription of the GrIS in subsequent climate model experiments (e.g. the second phase of PlioMIP).

2. Methods

2.1 Climate Model Forcing (PlioMIP)

2.1.1 The PlioMIP ensemble

In order to systematically examine uncertainties in numerical model predictions of the mPWP, ~~the Pliocene Model Intercomparison Project (~~PlioMIP ~~;~~ (Haywood et al., 2010; 2011a) was initiated as a component of PMIP (Palaeoclimate Model Intercomparison Project). PMIP's aim is to provide a means for co-ordinating palaeoclimate modelling and model-evaluation activities in order to understand the mechanisms of climate change and the role of climate feedbacks under past climate conditions (Braconnot et al., 2012). Previous comparisons of Pliocene simulations had been limited to at most three different climate models and had incorporated different approaches to implementing the Pliocene boundary conditions (e.g. Haywood et al., 2000; 2009).

PlioMIP established the design for two initial experiments. Experiment 1 used atmosphere-only climate models (AGCMs) and is detailed fully in Haywood et al. (2010). Experiment 2 utilised coupled atmosphere-ocean climate models (AOGCMs) and is described in Haywood et al. (2011a). Here the atmospheric and topographic fields from both the AGCMs and the AOGCMs in PlioMIP (Table 1) will be used to force an offline shallow ice approximation ISM (BASISM; see Section 2.2).

The boundary conditions applied to all climate models ~~in Experiments 1 and 2~~ of PlioMIP are described specifically in Haywood et al. (2010) and Haywood et al. (2011a) respectively. In brief, both experiments utilised the US Geological Survey PRISM3 boundary condition data set (Dowsett et al., 2010). PRISM3 is an improved dataset in terms of data coverage compared to its predecessor (PRISM2; Dowsett et al., 1999) and includes information on monthly SSTs and sea ice distributions, vegetation cover, sea level, ice sheet extent and topography. Vegetation cover is based on the palaeobotanical reconstruction of Salzmann et al. (2008) and topography is derived from the Sohl et al (2009) palaeogeographic reconstruction. The PRISM3 ice sheets applied in the climate models were derived from offline ISM ~~ice sheet model~~ experiments forced with climatological fields from the Hadley Centre Atmosphere-only climate model (Fig. 1; HadAM3; Hill, 2009), and represent an ice sheet~~, which~~that is consistent with the rest of the PRISM3 reconstruction. For the AGCMs the SST and sea ice distribution was fixed according to PRISM3, whereas the AOGCMs predicted their own ~~mPWP~~ Pliocene sea surface conditions.

In all of the PlioMIP experiments, the atmospheric concentration of CO_2 was set to 405 *ppmv* (Haywood et al., 2010; 2011a). This is slightly higher than the previous standard PRISM2 level (400 *ppmv*), but still falls well within the uncertainty limits of current CO_2 proxy records (e.g. Pagani et al., 2010; Seki et al., 2010; Bartoli et al., 2011). All other trace gases were specified at a pre-industrial concentration and the selected orbital configuration was unchanged from modern (Haywood et al., 2010).

Each of the PlioMIP models were set-up with PRISM3 boundary conditions as described above and the run for a minimum integration length of 50 years for the AGCMs and 500 years for the AOGCMs. Average climatological forcing fields were derived from the final 30 years of the simulation. Each modelling group's standard pre-industrial simulation was used as a control run.

Details of participating groups and climate models can be found in Table 1. Simulations from seven AGCMs and eight AOGCMs were completed and results submitted to PlioMIP. ~~For Experiment 1 (AGCMs), seven modelling groups and for Experiment 2 (AOGCMs) eight modelling groups completed and submitted data from their model integrations.~~ The AGCMs and AOGCMs ~~models used in both Experiment 1 and 2~~ sample differing levels of complexity and resolution from higher-resolution IPCC AR5-class models, to intermediate resolution models (Haywood et al., 2013).

2.1.2 Climatological Forcing over Greenland

Greenland mean annual temperature and precipitation, and summer temperature anomalies between the mid-Pliocene and the pre-industrial for each of the PlioMIP AGCMs and AOGCMs are shown in Figures 2, 3 and 4. Over Greenland simulated mid-Pliocene climates from the AGCMs show an increase in mean annual temperature of between 11.9°C and 14.1°C ~~8.2°C and 10.1°C~~, whereas the range predicted from the AOGCMs is much greater (5.3°C to 12.8°C~~5.0°C °C~~; Table 3). For ~~Experiment 1~~the AGCMs, mid-Pliocene mean annual precipitation levels over the Greenland region (Table 3) increase compared to pre-industrial in ~~all but one~~ models ~~(MRI-AGCM)~~. ~~For Experiment 2, MRI-AOGCM shows no change in average precipitation, although spatially, the precipitation is distributed differently, with an increase in precipitation rates over East Greenland and a reduction in rates around the southern coastal regions (see Fig. 3). The seven other~~ All AOGCMs show an increase in mid-Pliocene precipitation of between ~~0.14~~ 0.2 mm day^{-1} and 0.8~~0.4~~ mm day^{-1}. Simulated mid-Pliocene summer temperatures were on average ~~8.5~~12.6°C warmer over Greenland ~~in Experiment 1~~for the AGCMs and ~~8.8~~12.3°C warmer in ~~Experiment 2.~~the AOGCMs. However, the average for the AOGCMs is lowered due to MRI-AOGCM simulating a warming of 4°C, whereas all other AOGCMs fall between 11.6°C and 15°C of warming in the Pliocene relative to the pre-industrial control simulation.

2.2 Ice Sheet Modelling Framework

In this study we used ~~the British Antarctic Survey Ice Sheet Model (~~BASISM~~)~~, which has previously been applied to study Pliocene ice sheets (Hill et al., 2007; Hill, 2009; Hill et al., 2010; Dolan et al., 2011). BASISM is a finite difference, thermomechanical, shallow ice approximation (SIA) ISM, utilising an unconditionally stable, implicit numerical solution of the non-linear simultaneous equations of ice flow. BASISM is similar to other SIA models described by Huybrechts (1990), Ritz et al. (2001) and Rutt et al. (2009) and a more detailed discussion of the numerical formulations behind BASISM can be found in Hindmarsh (1993, 1996, 1999, 2001). As well as the internal glaciological dynamics, interactions with the bedrock are simulated with a simple model of elastic rebound, with a rebound timescale of 3000 years (Le Meur and Huybrechts, 1996). The bedrock height for all initial conditions ~~are~~is recalculated using this model, on the assumption of isostatic equilibrium and then the bedrock is allowed to dynamically evolve adjust during subsequent ice sheet changes.

For this study, BASISM was run on a 20 km × 20 km grid, with 21 vertical layers, in a domain covering the modern grounded GrIS. The ISM is forced using climatological fields of mean annual temperature (Fig. 2) and precipitation (Fig. 3) and ~~mean summer~~warmest mean monthly temperature (July; Fig.4) from each of the PlioMIP ensemble members following the method of Hill (2009). An exponential function is used to convert temperatures into the number of positive degree days (Reeh, 1991), which shows a high level of correlation between warmest month temperatures and observations of present day melt (Hill, 2009). Bilinear interpolation was used to downscale the meteorological fields from the original climate model grid onto the higher resolution ISM grid. Downscaling is problematic in that the coarse horizontal resolution of the climate model is inadequate to resolve the steep topographic slopes around the edges of Greenland (Thompson and Pollard, 1997; Ridley et al., 2005). This is partly addressed by applying a uniform and constant lapse rate correction to resolve for the difference in climate model and ~~ice sheet model~~ISM topography, both in the initial conditions and as the ice sheet surface evolves during the simulation. The standard lapse rate used within BASISM is −6.0°C km^{-1}, which lies within modern observations of lapse rates on Greenland (Steffen and Box, 2001; Hanna et al., 2005). Currently, there is no known similar simple relationship between precipitation and altitude. Precipitation over the Greenland Ice Sheet is highly non-linear, with synoptic patterns of atmospheric circulation tending to drive patterns of accumulation (Schuenemann and Cassano, 2009). Combined model simulations and tree-ring isotopes have shown that the dominant patterns of Pliocene North Atlantic atmospheric circulation are likely to have remained similar to today (Hill et al., 2011). Although some direct effects of altitude and temperature will occur as the ice sheet evolves, one of the key changes will be feedbacks on atmospheric circulation, which can only be modelled in a coupled ice sheet–climate model (Mayewski et al., 1994). Where downscaling methods do exist (e.g. Ritz et al., 1997), the ratio of precipitation change with temperature change is poorly constrained (Charbit et al., 2002). Therefore, no correction for precipitation has been made within the ice sheet modelling experiments presented here.

The Positive Degree-Day (PDD) method was employed to convert the climate fields into a melt rate (Reeh, 1991; Braithwaite, 1995) and is well established in coupled atmosphere-ice sheet palaeoclimate modelling studies (e.g. DeConto and Pollard, 2003; Lunt et al., 2008a; 2008b; 2009). This technique assumes that the melting of the ice sheet surface can be fully described by three physical constants (melt rate or PDD factor of ice and snow and the maximum fractional refreezing rate (W_{max})) and the temperature record. Although many other factors could contribute this method has been shown to have some physical justification (Ohmura, 2001). Standard PDD parameters for ice ($\propto_i$) and snow ($\propto_s$) are set to $\propto_i$ = 8 mm day^{-1} °C and $\propto_s$ = 3 mm day^{-1} °C respectively, which is within observations of different modern day climates (Braithwaite, 1995). Further developments of the PDD method have been used in previous studies, but they rely on additional~~ further~~ glaciological parameters that may not ~~, which it is not clear whether they would~~ remain constant in palaeoclimate s~~imulation~~cenarios, thus it is unclear how to assign them for the Pliocene (Janssens and Huybrechts, 2000; Tarasov and Peltier, 2002)

The aforementioned "standard" glaciological parameters (i.e. lapse rate, and the PDD factors of ice and snow) used in BASISM were originally tuned for a HadAM3 experiment (Hill, 2009), so that the best representation of the modern GrIS and East Antarctic Ice Sheet (EAIS) were simulated. However, these parameter values are still poorly constrained and result in highly variable ice sheet volumes and extents depending on the exact values prescribed (Ritz et al., 1997; Lunt et al., 2008b; Stone et al., 2010). Stone et al. (2010) demonstrated that the ice sheet extent is predominantly dependent on the PDD factors and the ~~atmospheric ~~lapse rate and therefore we have chosen to vary these parameters in order to obtain an additional estimate of uncertainty on our ~~ice sheet model~~ISM reconstructions.

The typical annual lapse rate used for a variety of studies on Greenland (e.g. Ridley et al., 2005; Huybrechts and de Wolde, 1999; Vizcaíno et al., 2008) ranges from -6.0°C to -8.0°C km^{-1} and therefore here we will test values within this range (Table 2). The PDD parameter values for ice and snow vary much more within the literature and previous modelling studies. The standard value for ice used by many modellers is 8 mm day^{-1} °C (e.g. Huybrechts and de Wolde, 1999; Ritz et al., 1997), although Braithwaite (1995) suggested that the value could be as much as 20 mm day^{-1} °C. Modelling studies for the Pliocene Greenland (e.g. Lunt et al., 2008a) have tested a range of PDD parameters from *low* PDD factors ($\propto_i$ = 8 mm day^{-1} °C and $\propto_s$ = 3 mm day^{-1} °C; the same as BASISM standard) to very high PDD factors ($\propto_i$ = 64 mm day^{-1} °C and $\propto_s$ = 24 mm day^{-1} °C) and have shown that the higher end of these ranges do not lead to a good simulation of the modern Greenland ice sheet. Here we vary PDD factors conservatively between $\propto_s$ = 3 mm day^{-1} °C and $\propto_s$ = 6 mm day^{-1} °C for snow and $\propto_i$ = 5 mm day^{-1} °C and $\propto_i$ = 14 mm day^{-1} °C for ice (Table 2).

Although it is possible to use statistical methods such as Latin Hypercube Sampling (LHS) to define random plausible parameter sets within a given range (e.g. Stone et al., 2010), here we simply choose to co-vary parameters. Table 2 shows the parameter values tested here, which equals 48 parameter permutations for each simulation based on the forcing from one climate model. In every ISM simulation, absolute temperatures and precipitation values were used to force the ISM and no correction was made to account for temperature biases in each model's simulation of the pre-industrial (*cf.* Lunt et al., 2009). BASISM was run for 50 000 years, which is enough time for the simulated ice sheet to come into geometric and thermal equilibrium with the forcing climate.

Prior to simulating the Pliocene GrIS, control cases were run in order to enable an assessment of the modelling framework for the pre-industrial. For the pre-industrial simulations, BASISM was initialised from a modern ice configuration. Initially it is useful to determine whether the pre-industrial control climate from each model produces a sensible reconstruction of the present Greenland ice sheet using BASISM with the range of glaciological parameters that are identified in Table 2. In order to analyse the ice sheet geometries from the 48 experiments undertaken for each of the PlioMIP climate models, we have chosen two performance metrics to investigate for each model simulation. Following the methods of Stone et al. (2010), the difference in total ice volume compared to estimated modern volume will be used as an overall diagnostic of how well each simulation reconstructs the observations of ice thickness. The second performance metric will be the ~~normalised~~ Root Mean Square Error (RMSE), which is a measure of the spatial fit of the ice sheet thickness reconstruction over the Greenland domain. RMSE describes the magnitude of the differences between two fields (e.g. observed ice thickness and simulated ice thickness). In both cases, ~~zero~~ lower values ~~would~~ describe a ~~perfect~~ better match between the modelled and the observed GrIS. We use the digital elevation model (DEM) of Bamber et al. (2001) interpolated on to the ISM grid (20 km resolution) to calculate observed ice sheet volume and thickness. This technique will also allow the definition of optimal parameter sets (within the envelope of parameter values tested) which gives each forcing climate model the "best" estimate of the present GrIS. These parameter sets were than used with each of the climate forcings from the PlioMIP ensemble.

3. Results

~~3.1 Climatological Forcing over Greenland~~

~~Greenland mean annual temperature and precipitation, and summer temperature anomalies between the mid-Pliocene and the pre-industrial for each of the PlioMIP AGCMs and AOGCMs are shown in Figures 2, 3 and 4. Over Greenland simulated mid-Pliocene climates from the AGCMs show an increase in mean annual temperature of between 8.2°C and 10.1°C, whereas the range predicted from the AOGCMs is much greater (5.0°C to 9.6°C; Table 3). For Experiment 1, mid-Pliocene mean annual precipitation levels over the Greenland region (Table 3) increase compared to pre-industrial in all but one model (MRI-AGCM). For Experiment 2, MRI-AOGCM shows no change in average precipitation, although spatially, the precipitation is distributed differently, with an increase in precipitation rates over East Greenland and a reduction in rates around the southern coastal regions~~

~~(see Fig. 3). The seven other AOGCMs show an increase in mid-Pliocene precipitation of between 0.14 mm day^{-1} and 0.4 mm day^{-1}. Simulated mid-Pliocene summer temperatures were on average 8.5°C warmer over Greenland in Experiment 1 and 8.8°C warmer in Experiment 2.~~

3.1~~2~~ Greenland Ice Sheet Simulations

3.1~~2~~.1 Pre-Industrial Control Greenland Ice Sheets

For the pre-industrial control experiments, BASISM was initialised from the modern GrIS. Figures 5a (AGCMs) and 5b (AOGCMs) summarise the sensitivity of modelled GrIS volume to the three tuneable glaciological parameters (Table 2). For most of the PlioMIP climate model inputs, the choice of parameter values for atmospheric lapse rate and the PDD factors of ice and snow have little impact on the resulting GrIS volume (with the exception of HadAM3 and the fully coupled version of MIROC where the final volume changes with the choice of some different parameter sets; Fig. 5b). This is due to the modern ablation zone being constrained to the steep slopes on the periphery of the ice sheet and the constraints applied at the ice sheet grounding line. The parameter set for each PlioMIP model which gives the optimal ice sheet in terms of total ice volume or RMSE of ice thickness for steady-state conditions in comparison to modern observations is also shown in Figures 5a and 5b. Based on the diagnostics chosen here, the optimal parameter sets are never equal to the standard parameter values used within BASISM, although the impact of this on the pre-industrial GrIS is minimal.

For ease of comparison, if we consider using the standard BASISM parameters, all forcing climatologies produce a GrIS which is similar to modern observations. However, the ISM consistently overestimates volume by between +3% and +17%. Comparing the spatial differences between Bamber et al. (2001) and the PlioMIP-based ISM simulations, there are similar biases in elevation (Fig. 6) between the different climate forcings. Over central Greenland, some BASISM simulations produce ice sheets that are too low (~200 to 400 m) in comparison to observations (Fig. 6) although others (notably CAM3.1, COSMOS (AGCM and AOGCM), NorESM (AGCM and AOGCM)) are very close to observations in these regions. Consistent with other ISMs (e.g. Koenig et al, 2014b), all BASISM simulations produce ice sheets that are too high (up to ~800 m) at the ice sheet margins (Fig. 6). These largest deviations from observations occur in the regions of fast ice sheet flow around the ice sheet margins. ~~and~~ These reflect the inherent problems with both the relatively coarse resolution climate model and the ~~ice sheet model~~ISM at simulating areas of steep topography and complex dynamics ~~(e.g. those associated with steep topography)~~. Additionally, as a large proportion (~40%) of the ice loss in Greenland occurs through iceberg calving (Huybrechts et al., 1991) and such grounding line physics are omitted from this SIA ISM, it is expected that ice loss at the margin would be underestimated (Fig. 6). For smaller simulated ice sheets where ice terminates on land (such as those in the Pliocene e.g. PRISM3; Fig. 1), problems associated with ice dynamics such as calving are anticipated to have less of an influence on the reconstruction.

The ranking between the simulations depends upon the choice of metric (volumetric or spatial) and thus n~~N~~o one climatological forcing stands out as giving the best representation of the present GrIS. ~~,~~ ~~as the ranking between simulations depends on the choice of metric (volumetric or spatial).~~ Therefore these metrics will be considered separately in the analysis of Pliocene results. RMSE values for each PlioMIP model based on the optimal parameter sets range from 250 to 305 m and there is no discernible difference in skill at reproducing the modern GrIS between the AGCMs (Fig. 5a) and the AOGCMs (Fig. 5b). Considering both the AGCMs and AOGCMs, the parameter set for each model which gives the smallest RMSE, simulates a difference in volume between the models of 3.01 × 10^6 km^3 and 3.47 × 10^6 km^3. Using the standard parameter set used in BASISM, the volume difference for the pre-industrial is similar (3.02 × 10^6 km^3 and 3.44 10^6 km^3). In summary, none of the simulated ice sheets show any significant biases beyond those inherent when using a SIA ISM (see also Ritz et al. 1997; Saito and Abe-Ouchi, 2005). This provides confidence in the results of the Pliocene ISM simulations using the same modelling framework.

3.~~2~~1.2 Pliocene Greenland Ice Sheets

For the mid-Pliocene runs, BASISM was initialised from the PRISM3 ice configuration (Dowsett et al., 2010; Fig. 1), consistent with the climate model forcing. Figure 7 shows the simulated GrIS volume for each of the PlioMIP ensemble members using the different glaciological parameters listed in Table 2. In contrast to the pre-industrial ice sheets, Pliocene simulations are much more sensitive to the chosen parameter values within the ISM. This is consistent with results presented by Robinson et al. (2011) using a different modelling framework, which show that the modern GrIS is less sensitive to changes in melt parameters than ice sheet reconstructions for the warmer-than-modern Eemian Interglacial (ca. 130-115 ka BP). In all cases, the use of the standard, the volumetrically optimal or the spatially optimal parameters within BASISM has a significant impact on the resulting Pliocene GrIS reconstruction (Fig. 7).

Figure 8 shows the surface mass balance (SMB) calculated by BASISM for the PlioMIP climatologies from the initial ISM time-step. BASISM simulates a positive SMB over the PRISM3 ice sheet region for the majority of PlioMIP climate forcings and over the southern and western parts of Greenland, net ablation of up to 10 m yr^{-1} is predicted. In MRI-CGCM2.3 (AOGCM), the cold summer Pliocene temperatures (Fig. 4; Table 3) mean that there is accumulation over most of the landmass of Greenland (Fig. 8). Conversely, the high summer temperatures exhibited in the NorESM-L models means that the GrIS area experiences only ablation, even over the centre of the PRISM3 GrIS.

Figure 9 shows the spatial distribution of the GrIS when BASISM (standard parameter set; red dots in Fig. 7) is forced with atmospheric input fields from each of the PlioMIP models. These results show large differences in both the ice thickness and extent from one simulation to another. In Experiment 1 uUsing the AGCMs, ice cover ranges from no ice (NorESM-L) to modern extent (COSMOS, MIROC4m and MRI-CGCM2.3). The absence of ice in the NorESM-L reconstruction is due to the fact that summer temperatures remain above freezing even when a lapse rate correction has been applied (to account for the differences in altitude between the GCM and the ISM grid). Therefore, no ice is able to survive the melt season in this simulation (Fig. 9). The ice sheet reconstructions using CAM3.1 (0.77 $\times 10^6$ km^3) and LMDZ5A (1.47 $\times 10^6$ km^3) provide ice sheets that are comparable in terms of volume to the PRISM3 GrIS (1.07 $\times 10^6$ km^3), although the distribution of ice is most similar in LMDZ5A (Fig. 9).

All AOGCMs produce some ice over Greenland during the mPWP (Fig. 9) and seven of the eight reconstructions show a reduction in volume in comparison to the GCM specific pre-industrial counterpart (Table 4). Ice is distributed in these seven reconstructions as two ice caps, one in the South of Greenland and one spreading out from the mountains of East Greenland. The simulation performed using MRI-CGCM2.3 (AOGCM) produces a GrIS of modern extent with an overall increase in modelled volume relative to the pre-industrial control (+6.3%; Table 4). This is consistent with the MRI-CGCM2.3 (AOGCM) simulated Pliocene temperature over Greenland, which is on average 9°C warmer than the MRI-CGCM2.3 pre-industrial. Nevertheless, the absolute Pliocene temperatures remain much colder than those simulated within the rest of the ensemble and are actually more akin to the range of pre-industrial temperatures simulated by the other models (Table 3). At the other extreme, NorESM-L produces a GrIS which is reduced in areal extent by 1.41 $\times$ 10^6 km^2 (equivalent to a simulated sea level increase of >7m). GISS ModelE2-R, HadCM3 and IPSLCM5A produce relatively similar ice sheet configurations over Greenland with the Northern ice cap not extending across to West Greenland. However, the ice sheets reconstructed by CCSM4, COSMOS and MIROC4m either reach or stretch to within ~60 km of the Baffin Bay coastline (Fig. 9). In terms of areal extent and volume the IPSLCM5A and the GISS ModelE2-R ice sheet reconstructions are the closest to the original PRISM3 GrIS.

4. Discussion

To date, only a few studies (e.g. Charbit et al., 2007; Quiquet et al., 2012; Yan et al., 2013) have tested the sensitivity of an ISM to atmospheric input fields explicitly, with more focussing on parametric uncertainty within ice sheet modelling (e.g. Marshall et al., 2002; Tarasov and Peltier, 2004; Hebeler et al., 2008; Stone et al., 2010). In this study we have tested the climate model dependency of ice sheet reconstructions using output from multiple Pliocene climate models. The simulated mid-Pliocene GrISs reveal significant differences from one simulation to the other with respect to both the simulated ice volume and ice-covered area, and to the shape and spatial distribution of the ice sheet.

4.1 Understanding Climate Model Differences

By comparing the ISM output (Fig. 9) with GCM-predicted mid-Pliocene climate forcing (Figs. 2 to 4) and the calculated SMB fields (Fig. 8), it is clear that some of the major variations are reflected in the differences in temperature and precipitation fields amongst the model ensemble. This is in agreement with the study of Charbit et al. (2007) who demonstrated that variability in climate forcing through the last glacial-interglacial cycle induced large differences in simulated Northern Hemisphere ice sheets.

In order to better understand the mechanisms which cause inter-climate model differences in temperature, a more in-depth analysis is required of how changes in the ~~balance of energy~~energy balance leads to a redistribution of global heat (e.g. Heinemann et al., 2009; Lunt et al., 2012). Hill et al. (2014) have performed such an analysis on the AOGCM (Experiment 2) results from PlioMIP and have shown that the dominant control on annual mean temperature changes in the Arctic regions is related to the clear sky albedo in each model. All AOGCM simulations show ~~a~~that the strongest warming signals come from clear sky albedo (α), although the range in the magnitude of this warming is large (3-12°C; Hill et al., 2014). Clear sky albedo reflects changes on the Earth surface such as vegetation, snow cover and ice (both terrestrial ice and sea ice).

Figures 10 and 11 show the clear sky albedo values for the pre-industrial and mid-Pliocene simulations respectively from within the entire PlioMIP ensemble. The clear sky albedo value for each model is relatively similar for the pre-industrial simulations (except MRI-CGCM2.3 (AOGCM); Fig. 10), although there are differences in the albedo values at the margins of the ice sheets. Whilst this is sometimes linked to the resolution of the climate model giving either a finer (e.g. CCSM4 AOGCM) or a coarser (e.g. MRI-CGCM2.3 AOGCM) representation of albedo around Greenland, it can also be attributed to the different albedo properties of snow in each of the climate models (Table 5). For example, some climate models have deep-snow albedo values that are dependent on temperature (e.g. HadCM3, MRI-CGCM2.3 and COSMOS) but the range of maximum and minimum albedo values are not always identical (e.g. ~~α_{min} in~~ COSMOS is 0.6 whereas in MRI-CGCM2.3~~, α_{min} =~~it is 0.64). Moreover not all climate models account for factors which influence snow albedo such as the aging of snow or the radiative effects of darkening snow. The differences in the snow albedo schemes implemented in the ensemble may help to explain the differences shown in the Pliocene experiments especially over the GrIS region (Fig. 11).

In the ice-free regions of Greenland prescribed in PlioMIP, modelling groups were asked to implement the Salzmann et al. (2008) vegetation reconstruction. Due to the challenging nature of this task, different implementation methods were used within the modelling groups. The vegetation distribution was given to the groups in terms of the BIOME4 biome or mega-biome types (Salzmann et al., 2008). However, most modelling groups were unable to implement this exactly and instead mapped the plant-functional types onto their own biome scheme. In some cases (e.g. with the GISS ModelE2-R) this meant that distinct biome types within BIOME4, became merged into broader categories within an individual model scheme (Chandler et al., 2013). It is likely therefore that the albedo properties of the altered vegetation types could be quite different between models, which may be an important factor in the clear sky albedo differences shown in Figure 11.

The impact of differing albedo schemes over Greenland can be seen clearly in the MRI-CGCM2.3 (AOGCM) reconstruction of the mid-Pliocene GrIS (Fig. 9). Here the high albedo values relative to other models are also associated with much colder Pliocene temperatures (comparable with most pre-industrial simulations; Table 3) and lead to the reconstruction of a modern-sized Pliocene GrIS (Table 4; Fig. 9). High albedo values in the AOGCM version of MRI-CGCM2.3 are also consistent with results from Hill et al. (2014), which show this model as having the least contribution to Pliocene warming from clear sky albedo.

It is also useful to consider differences in predicted sea-surface temperatures (SSTs) and sea-ice around the Greenland region in the AOGCMs. Hill et al (2010) and Koenig et al. (2014) have shown minimal and large responses respectively of the GrIS to fixed SSTs within a climate model. Whilst these studies are not directly comparable (due to the use of different modelling frameworks and different initial conditions), Hill et al. (2010) suggest that the GrIS volume is relatively insensitive to changes in SSTs, with alterations in precipitation being the dominant forcing of the small changes (<20% of present GrIS volume). However, Koenig et al. (2014) have demonstrated a greater sensitivity of the GrIS to changes in temperature incurred by fixed SST and sea ice boundary conditions in the climate model. ~~Whilst some studies have shown differing degrees to which simulations of the GrIS are affected by fixing SSTs and sea-ice (e.g. Hill et al., 2010; Koenig et al., 2014a),~~ Also, Ballantyne et al (2013) have shown that Arctic continental temperatures in general (including those over Greenland) are highly sensitive to the prescription of sea-ice conditions within a model. For the AGCMs the Pliocene albedo values over the sea ice region around the coast of Greenland are very similar, reflecting the prescribed sea-ice conditions in these models (including sea-ice free in the summer; Fig. 11; see also Haywood et al., 2010). Minor albedo differences in the AGCMs are attributed to the varying sea-ice albedo schemes used in the models. Conversely, in the AOGCMs where the models can freely simulate sea ice conditions, there are significant differences in albedo values which reflect the changes in sea-ice predictions in this region. Howell et al. (in prep) have performed an in-depth analysis of the differences in Arctic sea-ice predictions within the

PlioMIP AOGCM ensemble. It is possible to draw correlations between some models sea-ice and GrIS reconstructions. For example, the higher summer temperature in July in NorESM-L may be partially attributed to the greatly reduced sea-ice and increased SSTs over sub-polar North Atlantic. Whereas using CCSM4, which retains a substantial sea-ice cover in the Arctic during summer, produces ~~is~~ one of the largest predicted GrISs (Fig. 9; Howell, *pers. comm*.). Whilst the differing conditions in the surrounding oceans offers some explanation as to the different GrIS predictions from the PlioMIP AOGCM ensemble, it does little to shed light upon the reasons for inter-model differences within the AGCMs. Thus it is difficult to promote sea-ice and SSTs as the sole fundamental control on the extent of the GrIS based on the results presented here.

One further potential contributor to the inter-model differences between ice sheet reconstructions could be the differences in resolution within the PlioMIP ensemble, as GCM resolution (within one model) has been shown to impact on the simulated climate (Roeckner et al., 2006). On one hand, there are multiple scenarios presented here where the GCM horizontal resolution is comparable (i.e. COSMOS and NorESM-L, MIROC4m and MRI-CGCM2.3), but the simulated ice sheet is very different (Fig. 9). However, it is also noticeable that the extent of the prescribed GrIS within each of the PlioMIP models is slightly different due to the model resolution (Table 1). This can be seen most clearly when considering the southward and eastward extent of the regions of accumulation (where the model predicts a positive SMB) in Figure 8. In general such regions of positive SMB track the shape of the prescribed PRISM3 ice sheet in the GCM and the overall area of accumulation will have an influence on the final GrIS volume.

Where possible it is also interesting to contrast the results obtained from using a fully-coupled version of the model to those obtained using the atmospheric component of the same model (Fig. 12). Six model lineages can be considered in this way; COSMOS (AGCM/AOGCM, Stepanek and Lohmann, 2012), HadAM3/HadCM3 (Bragg et al., 2012), LMDZ5A/IPSLCM5A (Contoux et al., 2012), MIROC4m (AGCM/AOGCM, Chan et al., 2011), MRI-CGCM2.3 (AGCM/AOGCM, Kamae and Ueda, 2012) and NorESM-L (AGCM/AOGCM, Zhang et al., 2012a; 2012b). As the AOGCM experiments incorporate a dynamic ocean, there is no reason to anticipate that the reconstructed ice sheets will necessarily be comparable when only the atmospheric component of the model is employed. Of the six climate models, four simulate a larger GrIS using the AGCM component than the AOGCM (COSMOS, LMDZ5A/IPSLCM5A, HadAM3/HadCM3 and MIROC4m; Fig. 9). Larger ice sheets are generally associated with the decrease in summer temperatures and increase in precipitation levels in the AGCMs (Fig. 12).

In summary, there are substantial differences in the predicted volumes of the GrIS when forced with multiple climate model predictions (performing a standard experiment), which suggests that the climate model dependency of ISM results is high. However, it is difficult to ascertain why the modelled differences occur between the PlioMIP simulations, although we have shown that the clear sky albedo within each model may be an important factor. In contrast, Koenig et al. (2014b) show much lower inter-ISM spread when reconstructing the GrIS during the Pliocene, which suggests that relative to climate model dependency, ISM dependency is low. This also gives us confidence that the BASISM-based ice sheet predictions presented here would also hold true if repeated with a different ~~ice sheet model~~ISM (see also Yan et al., 2014).

4.2 Understanding the Pliocene Greenland Ice Sheet

Our results show a high climate model dependency of ISM simulations over Greenland, which implies that the PRISM3 ice sheet configuration (Hill, 2009; Dowsett et al., 2010) is likely dependent on the climate model used within the modelling framework (in this case HadAM3). A better estimation of the GrIS during the mPWP might be derived from considering a 'mean' modelled ice sheet, rather than a single reconstruction. A number of studies have shown that a multi-model average often out-performs any individual model compared to observations (Knutti et al., 2010). This has been demonstrated for mean climate (Gleckler et al., 2008; Reichler and Kim, 2008), but also in regional climate model assessments of the mid-Pliocene (Zhang et al., 2013). A similar approach was taken for defining the Last Glacial Maximum (LGM) ice sheet configuration in the Northern Hemisphere. In the PMIP3/CMIP5 LGM experiments a blended product was obtained by averaging three different ice sheet reconstructions, because of the uncertainties associated with each individual reconstruction (PMIP3, 2010). Here we have calculated an un-weighted multi-model mean (MMM), which is the average of simulations in our multi-model ensemble, treating all models equally.

We have calculated MMMs for both the ice sheet configurations derived using the standard BASISM glaciological parameters and the parameter sets that give the best GrIS reconstruction in terms of modern volume. Figure 13a displays the differences between the calculated MMMs for the AGCM and AOGCM simulations. Present-day observations suggest that if the modern GrIS entirely deglaciated, global sea would rise by around 7.36 m (Bamber et al., 2013). The Pliocene GrIS MMM volumes are equivalent to a range in global sea level rise of 2.2 to 4.4 m (Fig. 13a). Due to the difficulties in creating a spatially consistent MMM GrIS, possible ice sheet configurations (taken from the BASISM ensemble of predicted ice sheets) that are approximately equal to the largest and smallest MMM volume are shown in Figure 13b. It is notable that the smallest MMM ice sheet is very similar to the PRISM3 GrIS boundary condition prescribed in the PlioMIP climate models (Fig. 1), with the exception of the ice cap on Southern Greenland.

There are nevertheless a number of problems with this approach that suggest that caution should be applied when interpreting these results. Firstly, given sea level records and proximal estimates of

Greenland ice, it is unlikely that a modern-extent GrIS prevailed during the warmest parts of the mPWP. In the case of the AOGCM 'best-fit' parameters, the removal of the large MRI-CGCM2.3 ice sheet reconstruction would make the ensemble spread significantly smaller and also impact upon the calculated MMM (the alternative MMM ice sheet reconstruction in this case would be equivalent to a 5.1 m sea level rise rather than a 4.4 m).

Secondly, Contoux et al. (~~submitted~~in review) highlight the possibility that the use of the PRISM3 GrIS as a climate model boundary condition for the experiments presented here might bias or precondition the subsequent ISM experiments towards a PRISM3-like GrIS. Contoux et al. (~~submitted~~in review) show that when an ice-free Greenland is prescribed in the IPSLCM5A climate model, the subsequent ISM reconstruction is smaller than the PRISM3 GrIS and restricted to the East Greenland Mountains and the southern tip of Greenland. This is supported by the inter-model assessment presented in Koenig et al. (2014b). When prescribing an ice-free Greenland during the Pliocene in HadAM3, five SIA ISMs reconstruct a mean ice loss equivalent to a ~7 m global sea level rise. However, when using the same set of boundary conditions to this study (i.e. PRISM3 ice in HadAM3), the contribution of the GrIS to sea level rise ranged between 2.2 m and 1.6 m as a MMM (see Koenig et al. 2014b for further details). This highlights the impact of the choice of initial ice configuration in the climate model. However, without a fully coupled ice-sheet-climate model, this is a difficult problem to overcome. Given the modelling framework adopted here, and the likely presence of ice on Greenland, it is essential to prescribe an ice sheet in the climate model, which requires a number of *a priori* assumptions regarding ice distribution. Not only does this have implications for our understanding of the GrIS during warm interglacials of the Pliocene, an incorrect representation of the ice sheets in general may have a negative impact when assessing global climate model simulations against proxy-data from the warm Pliocene (e.g. Dowsett et al., 2012; 2013; Haywood et al., 2013; Salzmann et al., 2013).

A final caveat to this research is derived from the uncertainty as to whether a good simulation of the modern GrIS (when compared to observations) necessarily implies a realistic representation of the Pliocene GrIS. Robinson et al. (2011) found that when simulating the Eemian GrIS (where significantly more constraints are available than for the Pliocene), the ISM simulation that gave the most realistic modern ice sheet, gave an entirely unrealistic ice sheet for the Eemian when compared with data. This highlights the need for further palaeodata constraints regarding the extent and thickness (where possible) of the Pliocene GrIS in order to thoroughly assess the results presented here.

4.3 Climate Model Boundary Conditions for PlioMIP Phase 2

The final aim of this study and the wider PLISMIP project (Dolan et al., 2012) is to inform decisions regarding the ice sheet boundary conditions prescribed in the second phase of PlioMIP (Haywood et al., in prep). The high climate model dependency of the GrIS shown here now brings into question the suitability of the PRISM3 GrIS in PlioMIP Phase 1, as this was the result of a one climate model/one ISM modelling framework. However, the broad range in the MMM ensemble presented here and the problems associated with *a priori* assumptions necessary to undertake this modelling framework suggest that the simple use of a MMM GrIS is inappropriate.

It is therefore likely that future GrIS reconstructions will be based on a combination of climate/ice sheet modelling results (e.g. Koenig et al., 2014b; Contoux et al., ~~submitted~~ in review and those presented here) and data-based constraints. Evidence for vegetation suggesting ice-free conditions can be found in North Greenland (Funder et al., 2001), at Ile de France (Bennike et al., 2002), on Ellesmere Island and the Canadian Archipelago (De Vernal and Mudie, 1989; Thompson and Flemming, 1996; Ballantyne et al., 2006; Csank et al., 2011), and these offer limited constraints on a mPWP GrIS reconstruction. More recently Bierman et al. (2014) have shown a preservation of a preglacial landscape under the centre of the GrIS at the site of the GISP2 (Greenland Ice Sheet Project 2) core. They suggest that the soils which formed at the base of the core (at the onset of Northern Hemisphere Glaciation around 2.7 Ma) could have been subaerially exposed for between 200,000 and 1 million years, ~~implying~~which has been suggested to imply that this region was potentially ice-free in the warm Pliocene. Additionally, a recent reassessment of pollen derived from ODP Hole 646B off southwest Greenland (de Vernal and Mudie, 1989) confirms that Southern Greenland would have been vegetated (boreal and cool-temperate conditions) during parts of the warm Pliocene (de Vernal, pers. comm.).

Combined, the proxy-based evidence and the modelling work done to date would suggest that a smaller ice cap (in relation to PRISM3), centred on the Eastern Greenland Mountains is the best available estimation of a warm interglacial Pliocene GrIS configuration. Clearly however, there is a critical need for further data pertaining to ice extent (e.g. Bierman et al., 2014) or potentially the Greenland climate (such as vegetation records) in order to more accurately~~to~~ constrain this reconstruction.

5. Conclusions

The Pliocene Ice Sheet Modelling Intercomparison Project (Dolan et al., 2012) was initiated in order to ascertain the degree to which ice predictions over Greenland are influenced by the choice of ISM and climate model. Whilst Koenig et al. (2014b) have shown that ISMs are generally relatively consistent in their predictions when all forced with same climatology, here we show that the choice of climate model significantly affects the predicted GrIS. Ice sheet reconstructions using forcing from the PlioMIP AGCMs and AOGCMs range from larger-than-modern to ice-free. Such a result demonstrates the difficulty in using only one climate model to draw conclusions regarding ice sheet stability in the warm Pliocene and highlights the need for an alternative ice sheet reconstruction going forward with PlioMIP Phase 2.

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Tables

Table 1: The short names of the PlioMIP climate models used to force BASISM, along with the atmospheric component resolution and the land-sea mask (LSM) scheme implemented by each model (Haywood et al., 2010). Regarding the LSM, 'preferred' refers to a LSM that has been entirely altered to meet the PlioMIP boundary conditions, whereas 'alternate' is where modelling groups have had to use more similar to modern LSM. More comprehensive details of each model and their implementation of the LSM can be found in Haywood et al (2013) and the individual references listed in this table.

Type	Model Name	Atmosphere Resolution (lat/lon)	References/Contributors	Preferred or Alternate LSM
AGCMs	CAM3.1	~2.8° × 2.8° (T42)	Yan et al. (2012)	Alternate
	COSMOS	3.75° × 3.75°	Stepanek and Lohmann (2012)	Preferred
	HadAM3	2.5° × 3.75°	Bragg et al. (2012)	Preferred
	LMDZ5A	1.9° × 3.75°	Contoux et al. (2012)	Preferred
	MIROC4m	~2.8° × 2.8° (T42)	Chan et al. (2011)	Preferred
	MRI-CGCM2.3	~2.8° × 2.8° (T42)	Kamae and Ueda (2012)	Alternate
	NorESM-L	~3.75° × 3.75° (T31)	Zhang and Yan (2012)	Alternate
AOGCMs	CCSM4	0.9° × 1.25~~2.5~~°	Rosenbloom et al. (2013)	Alternate
	COSMOS	3.75° × 3.75°	Stepanek and Lohmann (2012)	Preferred
	GISS ModelE2-R	2° × 2.5°	Chandler et al. (2013)	Preferred
	HadCM3	2.5° × 3.75°	Bragg et al. (2012)	Alternate
	IPSLCM5A	1.9° × 3.75°	Contoux et al. (2012)	Alternate
	MIROC4m	~2.8° × 2.8° (T42)	Chan et al. (2011)	Preferred
	MRI-CGCM2.3	~2.8° × 2.8° (T42)	Kamae and Ueda (2012)	Alternate
	NorESM-L	~3.75° × 3.75° (T31)	Zhang et al. (2012)	Alternate

Table 2: The three glaciological parameters and their values which are varied in the ice sheet modelling simulations. By varying each glaciological parameter independently, while holding the others constant, there are a total of 48 sensitivity experiments performed for each ice sheet model simulation.

Lapse Rate (°C km^{-1})	PDD Factor Snow ($\propto_i$; mm day^{-1} °C)	PDD Factor Ice ($\propto_s$; mm day^{-1} °C)
-6	3	5
-7	4	6
-8	5	8
	6	14

Table 3: Mean annual and summer temperature and mean annual precipitation values over the Greenland region for the PlioMIP climate models for the pre-industrial control experiments and the mPWP simulations. The climatological values have been calculated over the entire Greenland land mass as defined in the individual land-sea masks prescribed in the climate models. No ocean temperatures/precipitation values have been used.

		Abbrev. Model Name	Greenland Temperature (°C) Mean Annual	Mean Summer	Precipitation Mean Annual (mm day^{-1})
Experiment 1 (AGCMs)	Pre-Industrial	CAM3.1	-7.17	1.98	2.09
		COSMOS	-10.13	-0.92	2.07
		HadAM3	-12.01	-2.62	1.50
		LMDZ5A	-8.62	1.00	2.22
		MIROC4m	-10.21	0.78	1.85
		MRI-CGCM2.3	-9.65	-2.82	2.16
		NorESM-L	-7.27	1.83	1.89
	mid-Pliocene	CAM3.1	1.05	9.14	2.20
		COSMOS	-0.04	8.37	2.44
		HadAM3	-3.31	5.40	1.83
		LMDZ5A	-0.03	9.47	2.41
		MIROC4m	-0.60	8.02	2.05
		MRI-CGCM2.3	-1.15	5.79	2.13
		NorESM-L	2.29	12.21	1.92
Experiment 2 (AOGCMs)	Pre-Industrial	CCSM4	-10.8	0.35	2.07
		COSMOS	-10.36	-0.38	1.99
		GISS ModelE2-R	-12.34	-1.91	1.71
		HadCM3	-11.37	-0.77	1.67
		IPSLCM5A	-12.56	-0.89	1.7
		MIROC4m	-10.08	1.01	1.74
		MRI-CGCM2.3	-19.42	-9.98	1.52
		NorESM-L	-8.19	1.07	1.81
	mid-Pliocene	CCSM4	-5.78	7.14	2.28
		COSMOS	-1.22	9.03	2.39
		GISS ModelE2-R	-2.72	10.61	2.00
		HadCM3	-3.52	7.9	2.07
		IPSLCM5A	-4.09	8.55	1.97
		MIROC4m	-1.1	10.48	1.98
		MRI-	-12.85	-7.32	1.52

CGCM2.3			
NorESM-L	0.71	12.33	1.95

		Abbrev. Model Name	Greenland Temperature (°C) Mean Annual	Mean Summer	Precipitation Mean Annual (mm day^{-1})
AGCMs	Pre-Industrial	CAM3.1	-14.36	-1.76	1.56
		COSMOS	-18.22	-5.48	1.21
		HadAM3	-22.59	-8.82	0.92
		LMDZ5A	-20.97	-6.16	0.81
		MIROC4m	-19.44	-2.09	0.92
		MRI-CGCM2.3	-20.50	-12.23	1.04
		NorESM-L	-13.97	-1.71	1.33
	mid-Pliocene	CAM3.1	-2.45	8.95	2.01
		COSMOS	-4.26	7.41	2.00
		HadAM3	-8.98	4.09	1.70
		LMDZ5A	-6.89	7.69	1.92
		MIROC4m	-6.24	7.33	1.67
		MRI-CGCM2.3	-7.37	1.53	1.65
		NorESM-L	-0.71	13.00	1.70
AOGCMs	Pre-Industrial	CCSM4	-20.74	-5.08	1.25
		COSMOS	-18.32	-4.74	1.20
		GISS ModelE2-R	-14.78	-5.69	0.64
		HadCM3	-22.21	-10.14	1.05
		IPSLCM5A	-24.68	-7.76	0.56
		MIROC4m	-19.65	-2.46	0.94
		MRI-CGCM2.3	-28.18	-19.60	0.70
		NorESM-L	-15.86	-2.73	1.26
	mid-Pliocene	CCSM4	-13.58	5.42	1.60
		COSMOS	-5.93	8.08	1.83
		GISS ModelE2-R	-9.44	9.32	0.85
		HadCM3	-10.09	4.24	1.69
		IPSLCM5A	-11.89	7.12	1.34
		MIROC4m	-7.36	9.15	1.52
		MRI-CGCM2.3	-19.18	-15.59	0.96
		NorESM-L	-3.60	12.04	1.55

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Table 4: GrIS diagnostics for the PlioMIP simulations, including volume, sea level equivalent~~ height,~~ and ice area ~~and ice sheet maximum thickness~~ using the standard BASISM parameters. ~~Values are given as a difference from the GCM specific pre-industrial simulated ice sheet.~~Values are given as a difference from the simulated pre-industrial GrIS, when the same GCM pre-industrial forcing climatology is used. For example, negative volume or area means that the GrIS reduces in size compared to the GCM pre-industrial control. All simulated volumes (foe each parameter set) can be found in the Supplementary Information (Table S1).

	Model Name	Volume ($\times 10^6$ km^3)	S.L.E. (m)	Area ($\times 10^6$ km^2)	~~Maximum Ice Thickness (km)~~
AGCMs	CAM3.1	-2.70	-6.89	-1.10	~~-0.93~~
	COSMOS	0.14	0.36	-0.07	~~0.38~~
	HadAM3	-1.27	-3.25	-0.63	~~-0.13~~
	LMDZ5A	-1.67	-4.25	-0.85	~~0.19~~
	MIROC4m	0.19	0.49	-0.04	~~0.47~~
	MRI-CGCM2.3	0.22	0.57	-0.01	~~0.37~~
	NorESM-L	-3.46	-8.82	-1.66	~~-2.28~~
AOGCMs	CCSM4	-0.27	-0.68	-0.24	~~0.28~~
	COSMOS	-0.66	-1.68	-0.36	~~0.29~~
	GISS ModelE2-R	-1.89	-4.82	-0.96	~~0.02~~
	HadCM3	-1.73	-4.42	-0.83	~~-0.23~~
	IPSLCM5A	-1.85	-4.71	-0.91	~~-0.12~~
	MIROC4m	-0.834	-2.13	-0.44	~~0.29~~
	MRI-CGCM2.3	0.20	0.50	0.00	~~0.28~~
	NorESM-L	-3.12	-7.94	-1.41	~~-1.24~~

Model	**Snow albedo dependent on Temperature?**	**Aging snow simulated?**	**Wet/dry snow albedo properties considered?**	**Dependent upon the solar zenith angle?**	**Radiative effects of darkening snow considered?**	**General References**
CAM3.1	Yes – albedo dependent on temperature and spectral band to distinguish albedos for direct and diffuse incident radiation.	No	Yes – through temperature dependence	No – Ebert and Curry (1993)	*Unknown*	Collins et al. (2004)
CCSM4	*Unknown*	Yes – based on Warren and Wiscombe (1980)	*Unknown*	Yes	Yes (the SNow, ICe, and Aerosol Radiative model (SNICAR; Flanner and Zender, 2006))	Gent et al. (2011)
COSMOS	Yes – assumed to be a linear function of surface temperature. minimum $\alpha = 0.6$ for melting snow and maximum $\alpha = 0.8$ for cold temperatures	No	Yes – through temperature dependence	No	Yes – through temperature dependence	Roeckner et al. (2003)
GISS ModelE2-R	*Unknown*	Yes – following Loth and Graf (1998)	Yes – following Wiscombe and Warren (1980)	Yes – following Wiscombe and Warren (1980)	Yes – following Warren and Wiscombe (1980)	Schmidt et al. (2006)
HadAM3/ HadCM3	Yes – Uses land surface energy scheme MOSES1 (Cox et al., 1999) and albedo of snow is temperature dependent	No	No	*Unknown*	No	Cox et al. (1999)
LMDZ5A/ IPSLCM5A	No – snow albedo is dependent on snow age (as a function of time since the last snowfall). Land surface model is ORCHIDEE (Organizing Carbon and Hydrology In Dynamic Ecosystems, Krinner et al., 2005)	Yes	No	No	Yes – through the snow aging process	(Krinner et al., 2005)
MIROC4m	*Unknown*	Yes – following Wiscombe and Warren (1980)	Yes – following Wiscombe and Warren (1980)	Yes – following Wiscombe and Warren (1980)	Yes – following Wiscombe and Warren (1980)	Numaguti et al. (1997)
MRI-CGCM2.3	Yes – snow albedo ranges from from 0.8 (at temperatures < -4°C) to 0.64 (where the temperature of snow is 0°C; melting snow)	No	Yes – through temperature dependence	No	No	Yukimoto et al. (2006)
NorESM-L	*Unknown*	Yes	*Unknown*	Yes	Yes (the SNow, ICe, and Aerosol Radiative model (SNICAR; Flanner and Zender, 2006))	–

Model	Snow albedo dependent on Temperature?	Aging snow simulated?	Wet/dry snow albedo properties considered?	Dependent upon the solar zenith angle?	Radiative effects of darkening snow considered?	General References
CAM3.1	Yes - albedo dependent on temperature and spectral band to distinguish albedos for direct and diffuse incident radiation.	No	Yes – through temperature dependence	No – Ebert and Curry (1993)	*Unknown*	Collins et al. (2004)
CCSM4	Yes, snow albedo is an indirect function of temperature through the impact of temperature on snow grain size in the SNICAR model (SNow, ICe, and Aerosol Radiative model; Flanner and Zender, 2006)	Yes - through the SNICAR model	Yes - through the effective ice grain size which is altered by liquid water-induced metamorphism and refreezing	Yes	Yes - snow darkening occurs due to snow aging as well as black carbon and dust deposition (SNICAR)	Gent et al. (2011); Lawrence et al. (2011)
COSMOS	Yes – assumed to be a linear function of surface temperature. minimum α = 0.6 for melting snow and maximum α = 0.8 for cold temperatures	No	Yes - through temperature dependence	No	Yes – through temperature dependence	Roeckner et al. (2003)
GISS ModelE2-R	*Unknown*	Yes – following Loth and Graf (1998)	Yes - following Wiscombe and Warren (1980)	Yes – following Wiscombe and Warren (1980)	Yes – following Warren and Wiscombe (1980)	Schmidt et al. (2006)
HadAM3/ HadCM3	Yes – Uses land surface energy scheme MOSES1 (Cox et al., 1999) and albedo of snow is temperature dependent	No	No	*Unknown*	No	Cox et al. (1999)
LMDZ5A/ IPSLCM5A	No – snow albedo is dependent on snow age (as a function of time since the last snowfall). Land surface model is ORCHIDEE (Organizing Carbon and Hydrology In Dynamic Ecosystems, Krinner et al., 2005)	Yes	No	No	Yes – through the snow aging process	(Krinner et al., 2005)
MIROC4m	*Unknown*	Yes - following Wiscombe and Warren (1980)	Yes - following Wiscombe and Warren (1980)	Yes - following Wiscombe and Warren (1980)	Yes - following Wiscombe and Warren (1980)	Numaguti et al. (1997)
MRI-CGCM2.3	Yes – snow albedo ranges from from 0.8 (at temperatures < -4°C) to 0.64 (where the temperature of snow is 0°C; melting snow)	No	Yes - through temperature dependence	No	No	Yukimoto et al. (2006)
NorESM-L	As in CCSM4	As in CCSM4	As in CCSM4	As in CCSM4	As in CCSM4	As in CCSM4

Table 5: Details of snow albedo properties over land in each of the PlioMIP climate models.

Comment [AD1]: This table has been updated based on additional information

Figures

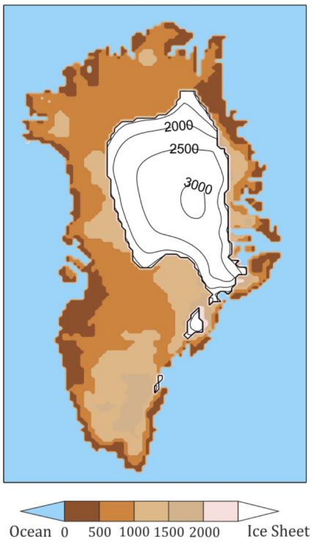


Figure 1: The PRISM3 Greenland ice sheet as simulated by BASISM (Hill, 2009; Dowsett et al., 2010). The forcing climatology for this ice sheet reconstruction is a HadAM3 simulation with PRISM2 boundary conditions (as described in Salzmann et al., 2008).

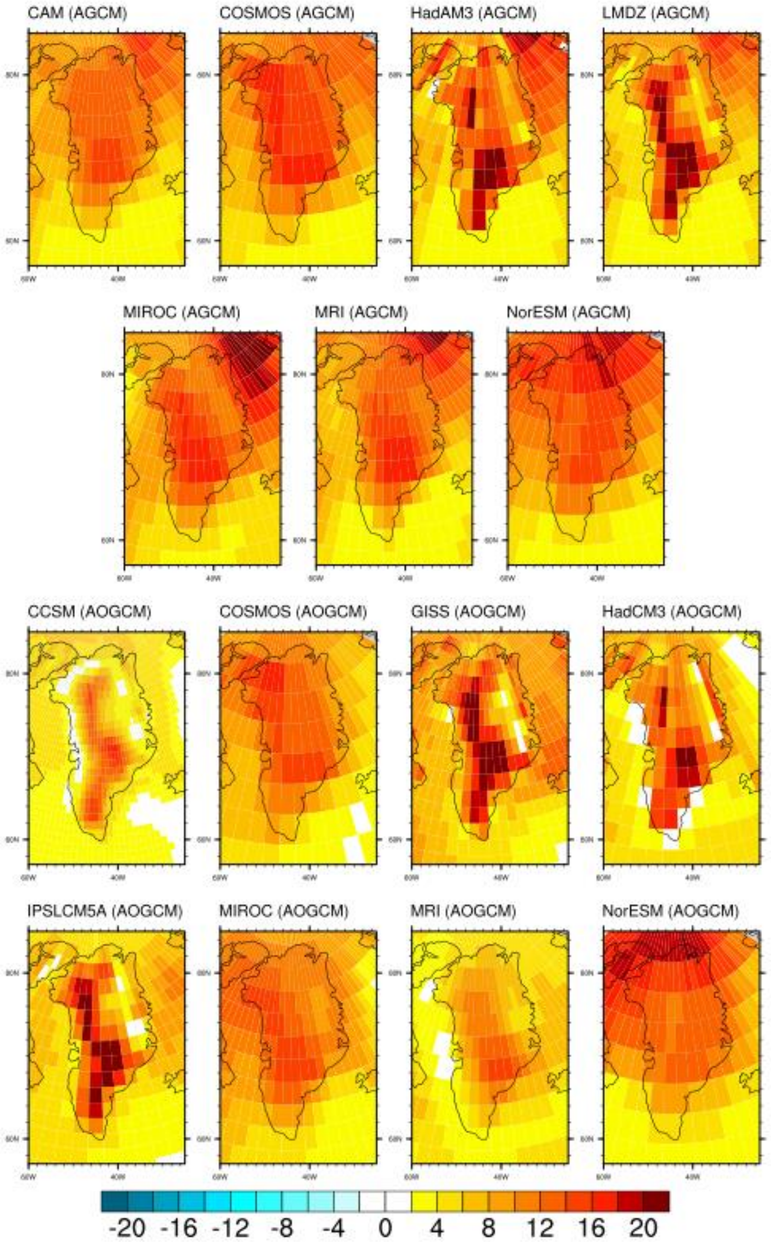


Figure 2: Pliocene minus pre-industrial mean annual surface air temperature (°C) over Greenland for the PlioMIP ensemble using atmosphere-only (AGCMs) and coupled atmosphere-ocean climate models (AOGCMs). Temperature plotted on the original climate model resolution.

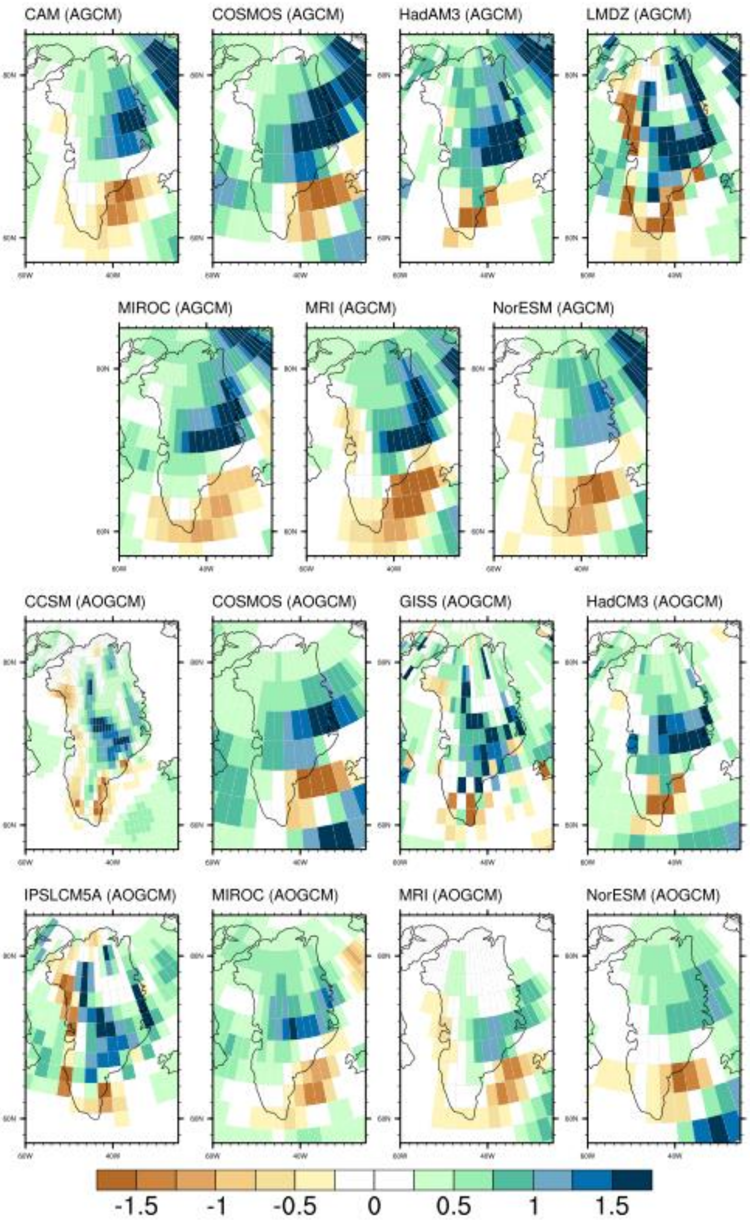


Figure 3: Pliocene minus pre-industrial mean annual precipitation (mm day^{-1}) over Greenland for the PlioMIP ensemble using atmosphere-only (AGCMs) and coupled atmosphere-ocean climate models (AOGCMs). Precipitation plotted on the original climate model resolution.

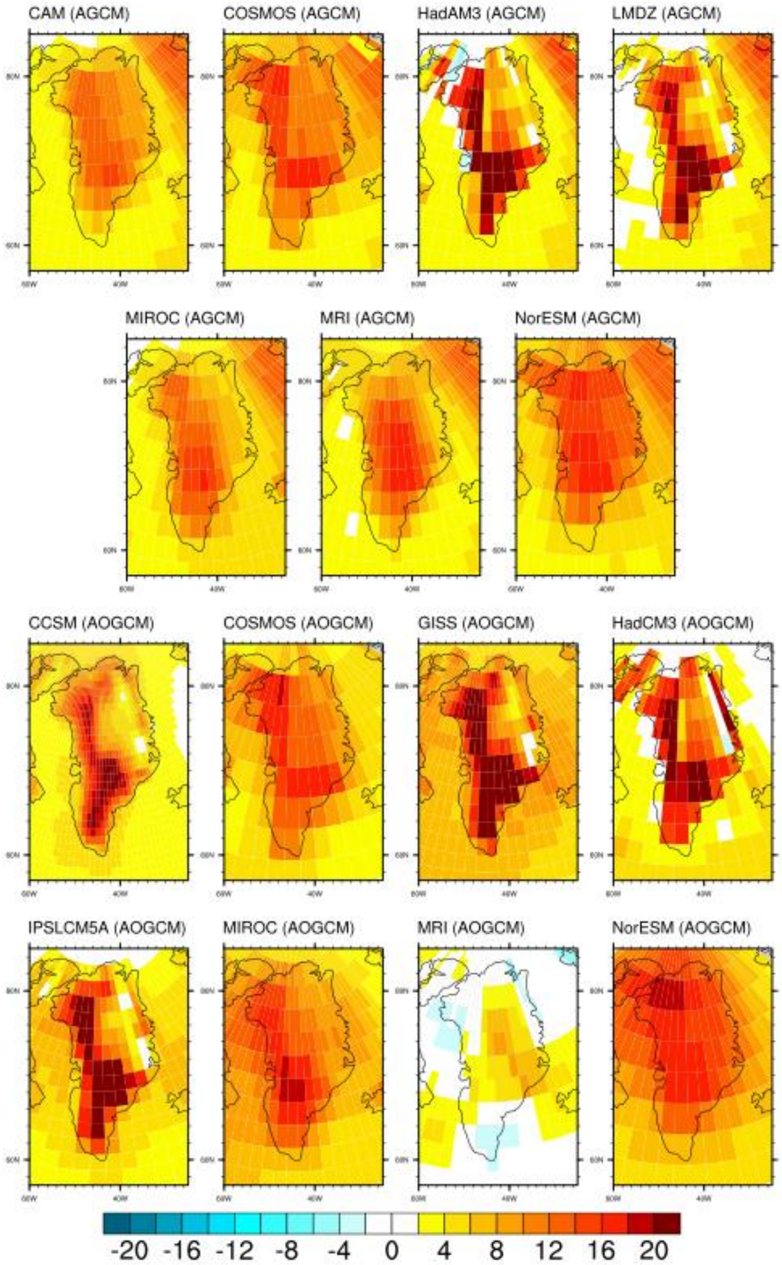
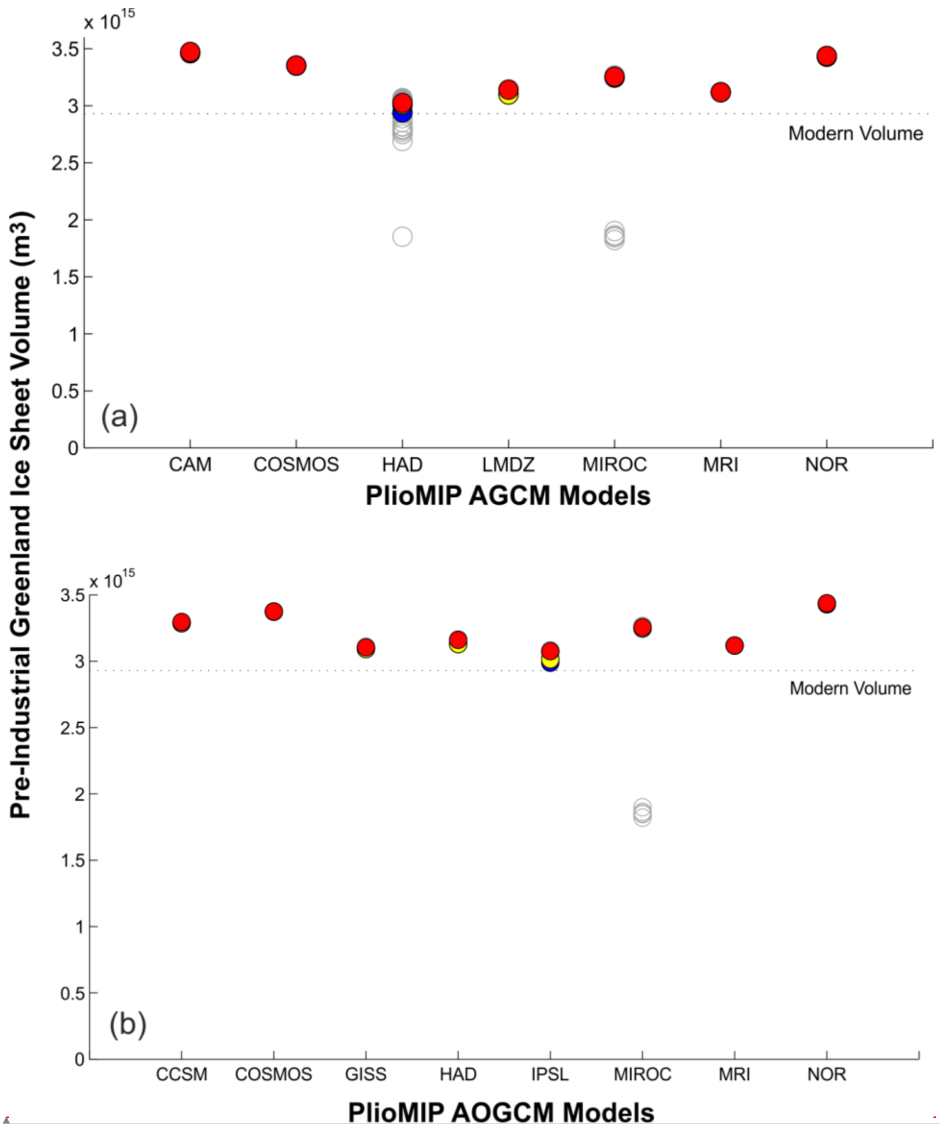


Figure 4: Pliocene minus pre-industrial mean July surface air temperature (°C) over Greenland for the PlioMIP ensemble using atmosphere-only (AGCMs) and coupled atmosphere-ocean climate models (AOGCMs). Temperature plotted on the original climate model resolution.



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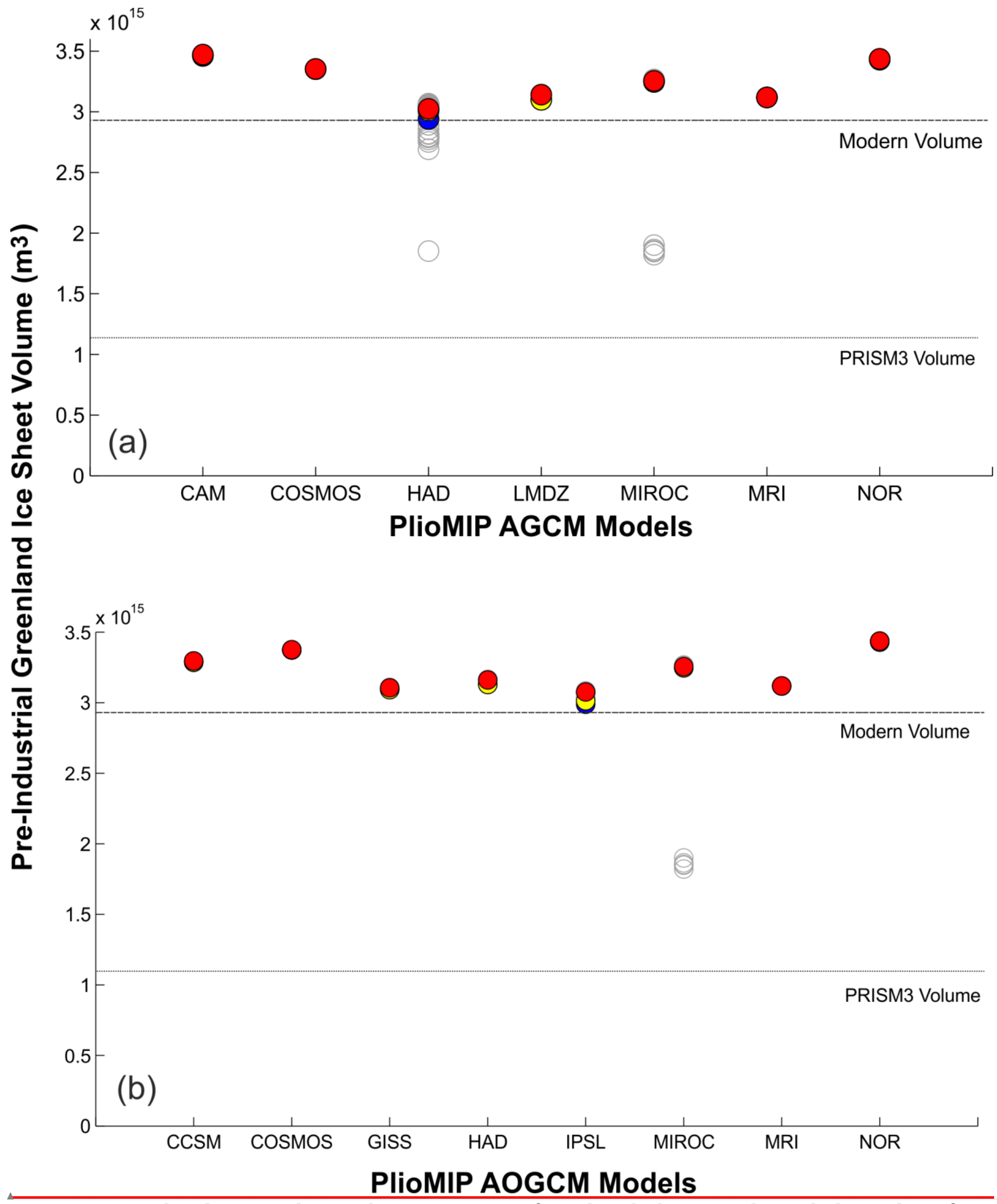

Figure 5: Simulated GrIS volume when BASISM is forced with the pre-industrial climatology from each of the (a) AGCM and (b) AOGCM PlioMIP models. The volume of the observed present-day GrIS (Bamber et al., 2001a) is shown for comparison. Red-filled circles show the standard parameter set used within BASISM ($\propto_i$ = 8 mm day^{-1} °C and $\propto_s$ = 3 mm day^{-1} °C, lapse rate = -6°C km^{-1}) and blue-filled circles show the parameter set that gives a volumetric reconstruction closest to observed. Yellow-filled circles show the parameter set that gives the lowest RMSE in terms of thickness. Grey circles show the sensitivity of the ice sheet volume to different values of lapse rate and the PDD

factors for ice and snow (see Table 2). The coloured circles are superimposed on the grey circles, so when the GrIS volume is similar, the grey circles (or individual colours) will not be visible.

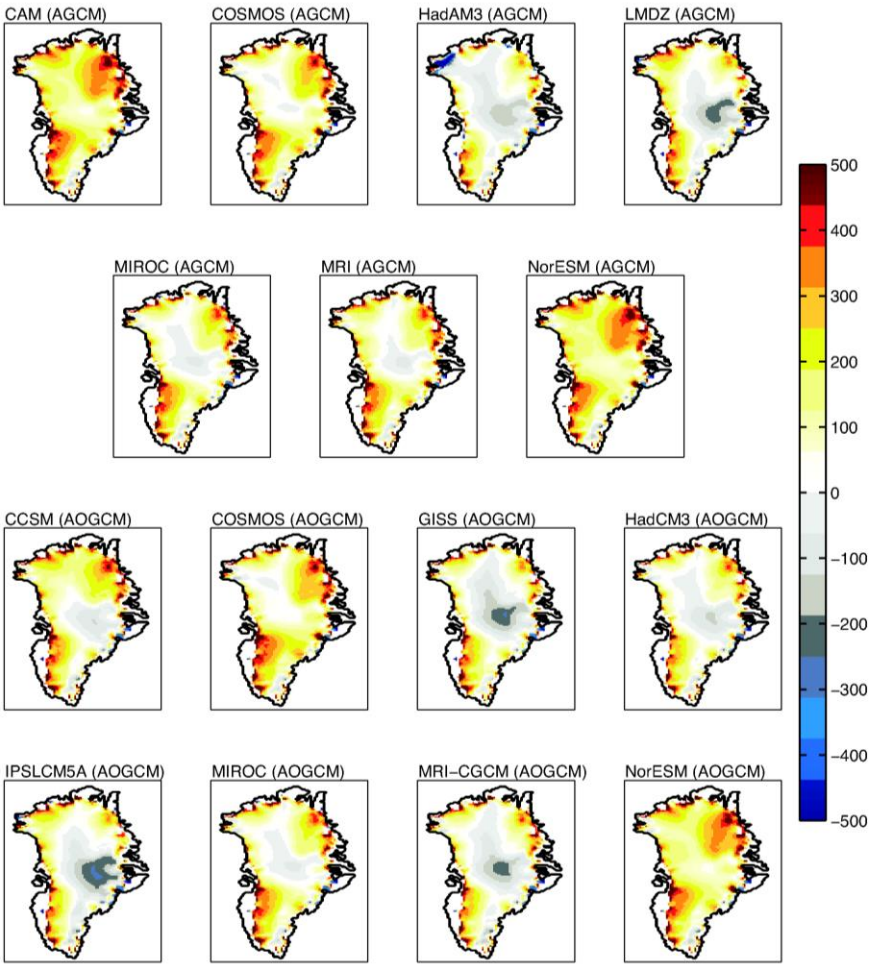

Figure 6: Ice sheet surface elevation (m) anomalies (model minus data) for the pre-industrial control relative to observed present-day GrIS (Bamber et al., 2001) for individual AGCM and AOGCM forcings. The BASISM simulations shown here were run using BASISM's standard glaciological parameters ($\propto_s$ = 3 mm day^{-1} and $\propto_i$ = 8 mm day^{-1}, lapse rate = -6˚C km^{-1}).

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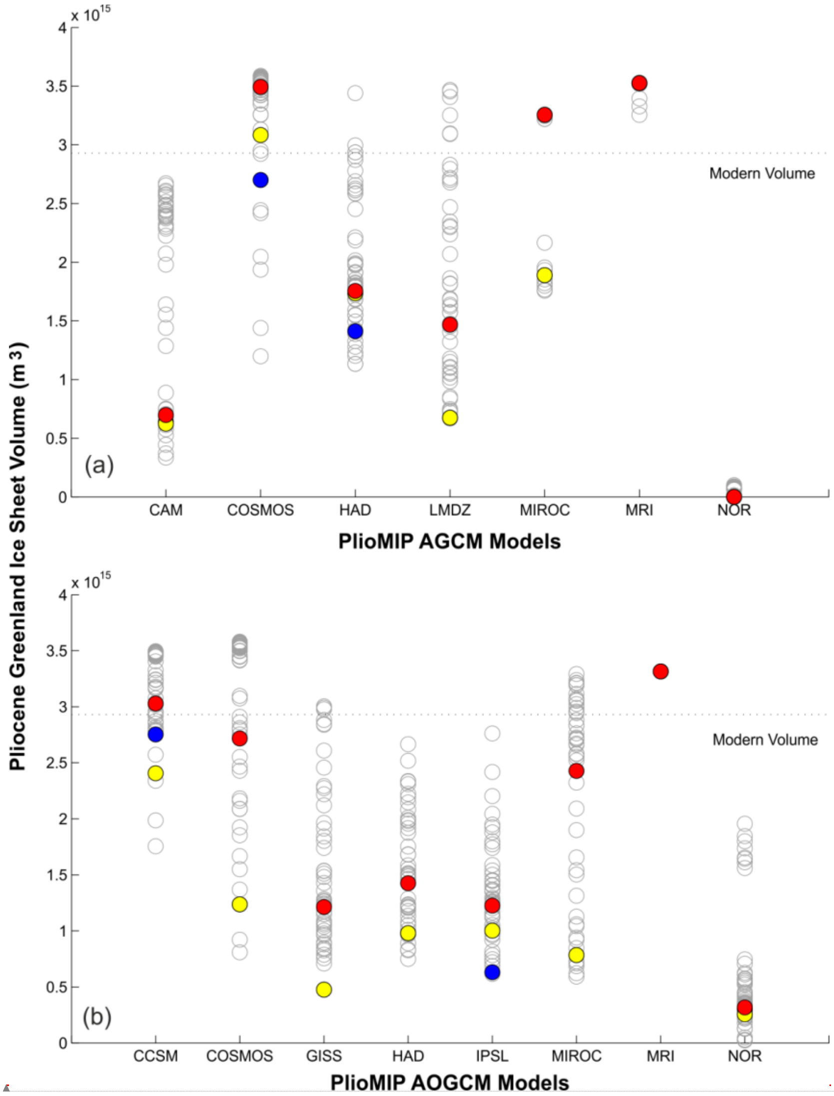

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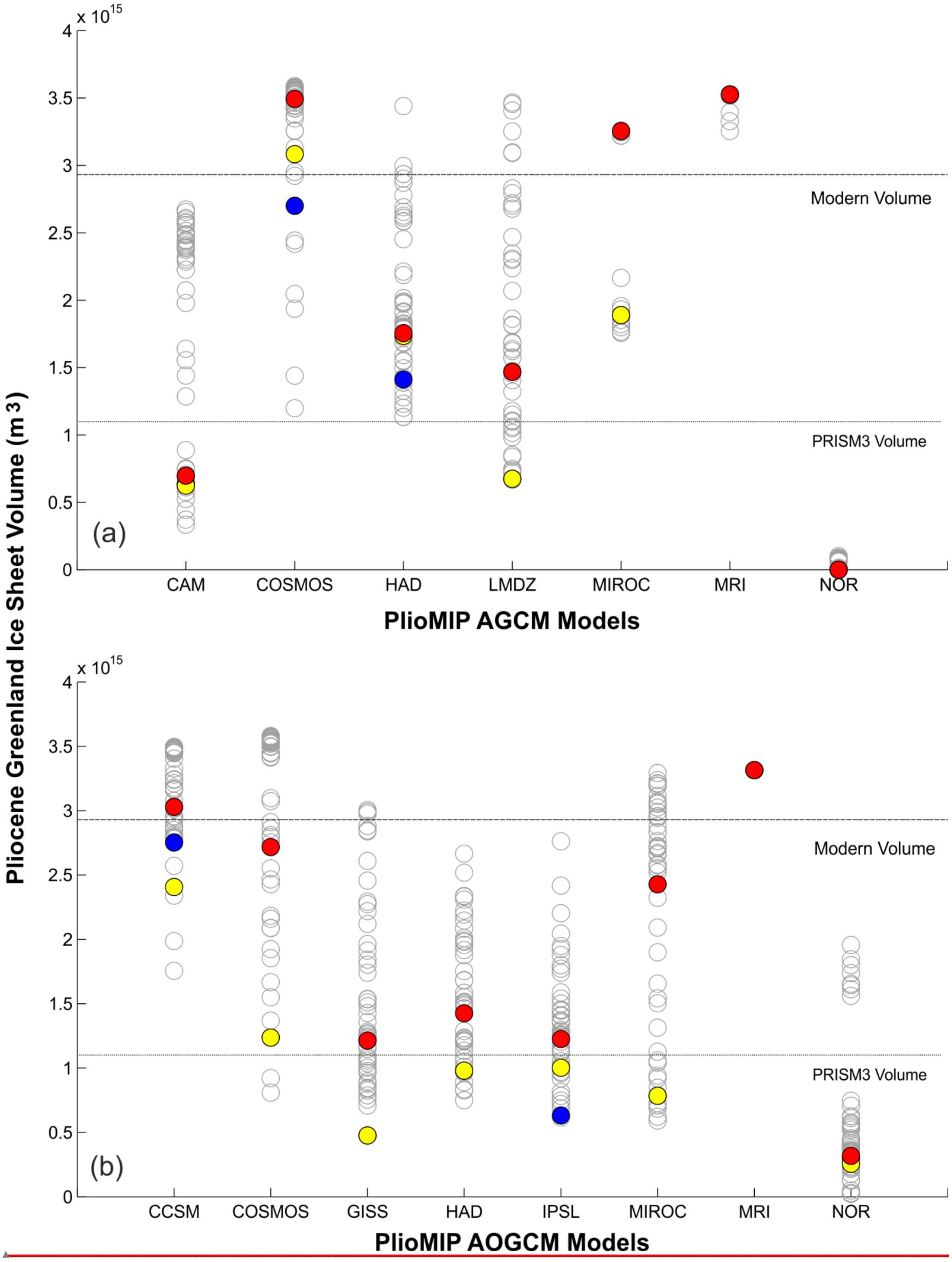

Figure 7: Simulated GrIS volume when BASISM is forced with the Pliocene climatology from each of the (a) AGCM and (b) AOGCM PlioMIP models. The volume of the observed present-day GrIS (Bamber et al., 2001a) is shown for comparison. Red-filled circles show the standard parameter set used within BASISM ($\propto_i$ = 8 mm day^{-1} °C and $\propto_s$ = 3 mm day^{-1} °C, lapse rate = -6°C km^{-1}) and blue-filled circles show the parameter set that gives a volumetric reconstruction closest to observed.

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Yellow-filled circles show the parameter set that gives the smallest RMSE in terms of simulated ice sheet thickness. Grey circles show the sensitivity of the ice sheet volume to different values of lapse rate and the PDD factors for ice and snow (see Table 2). The coloured circles are superimposed on the grey circles, so when the GrIS volume is similar, the grey circles (or individual colours) will not be visible.

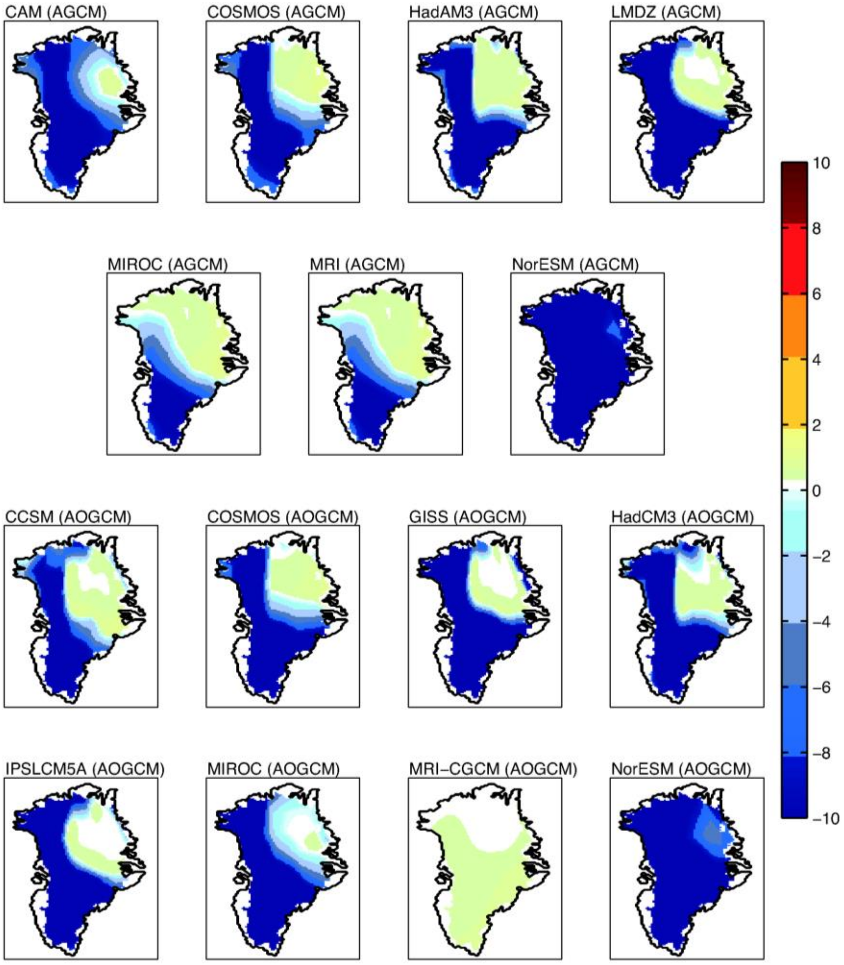


Figure 8: BASISM Surface Mass Balance (SMB; m yr^{-1}) predictions for the Pliocene (on the ISM grid) derived from the PlioMIP climatologies and using standard glaciological parameters ($\propto_i$ = 8 mm day^{-1} °C and $\propto_s$ = 3 mm day^{-1} °C, lapse rate = -6°C km^{-1}). The SMB is plotted for the first time step (prior to a lapse rate correction) and shows areas of ablation (negative SMB) and accumulation (positive SMB) based on the temperature and precipitation fields show in Figures 2, 3 and 4.

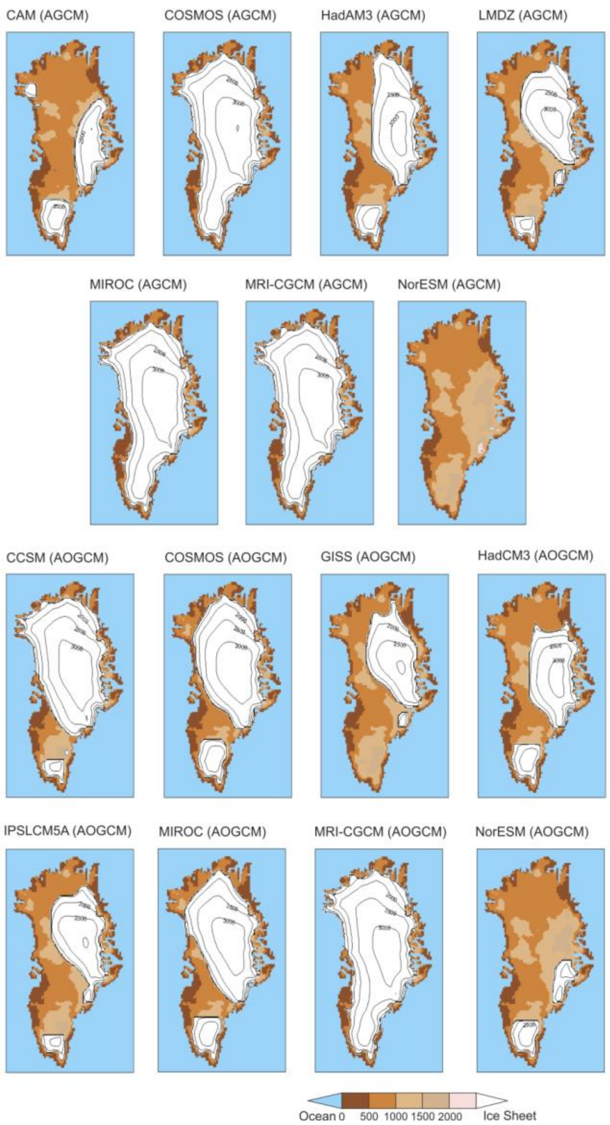


Figure 9: BASISM reconstructions of the Pliocene GrIS for individual AGCM and AOGCM forcings. All BASISM simulations were forced with climate model fields (i.e. temperature and precipitation) that were downscaled by a bilinear interpolation method to 20 km × 20 km resolution from the original model grid. GCM specific topography was also used and the ISM simulations were initialised from the PRISM3 ice sheet configuration (Fig. 1). The ice sheet configurations relate to the volumes (red-filled circles) shown in Figure 7 which use standard glaciological parameters.

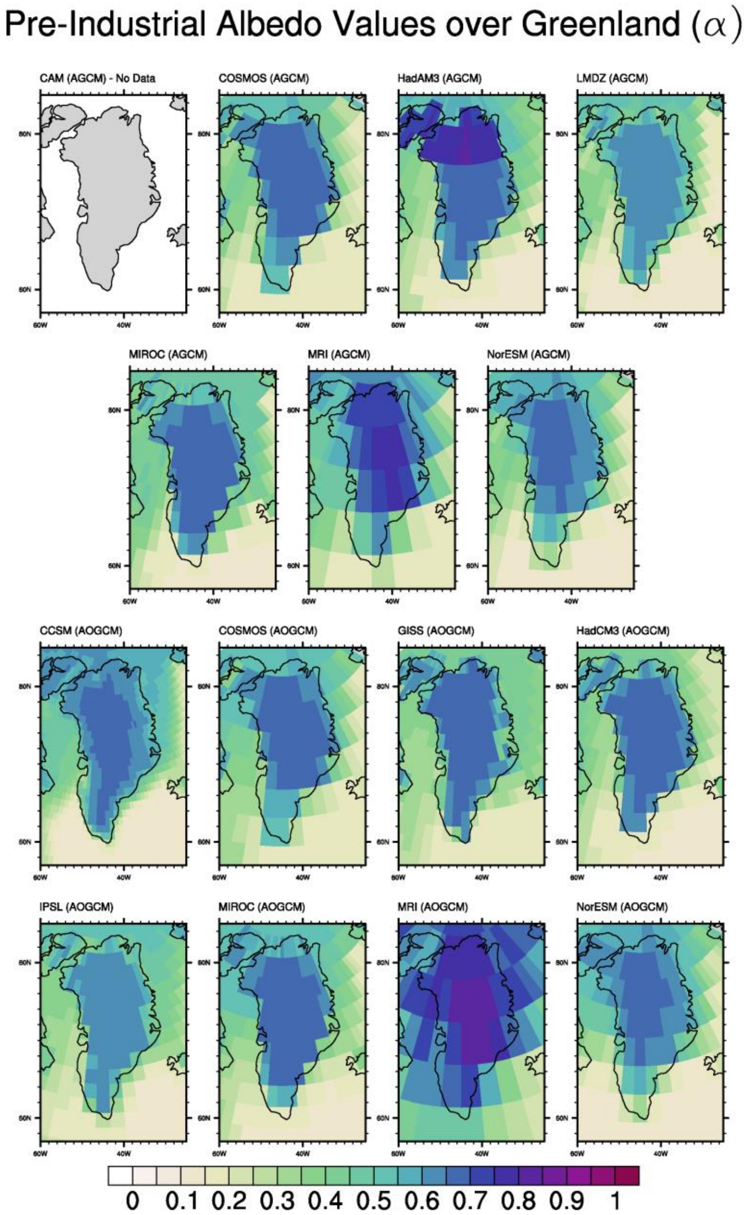


Figure 10: Pre-industrial annual mean clear sky albedo values over Greenland for PlioMIP models (where available).

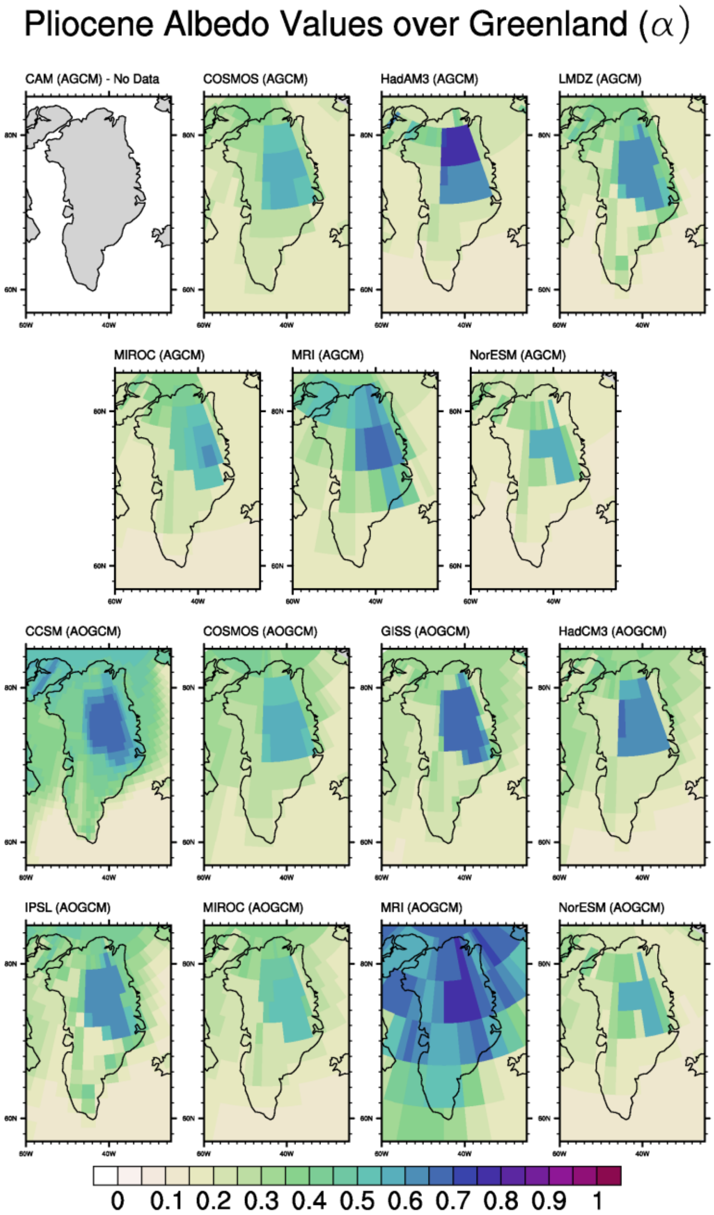
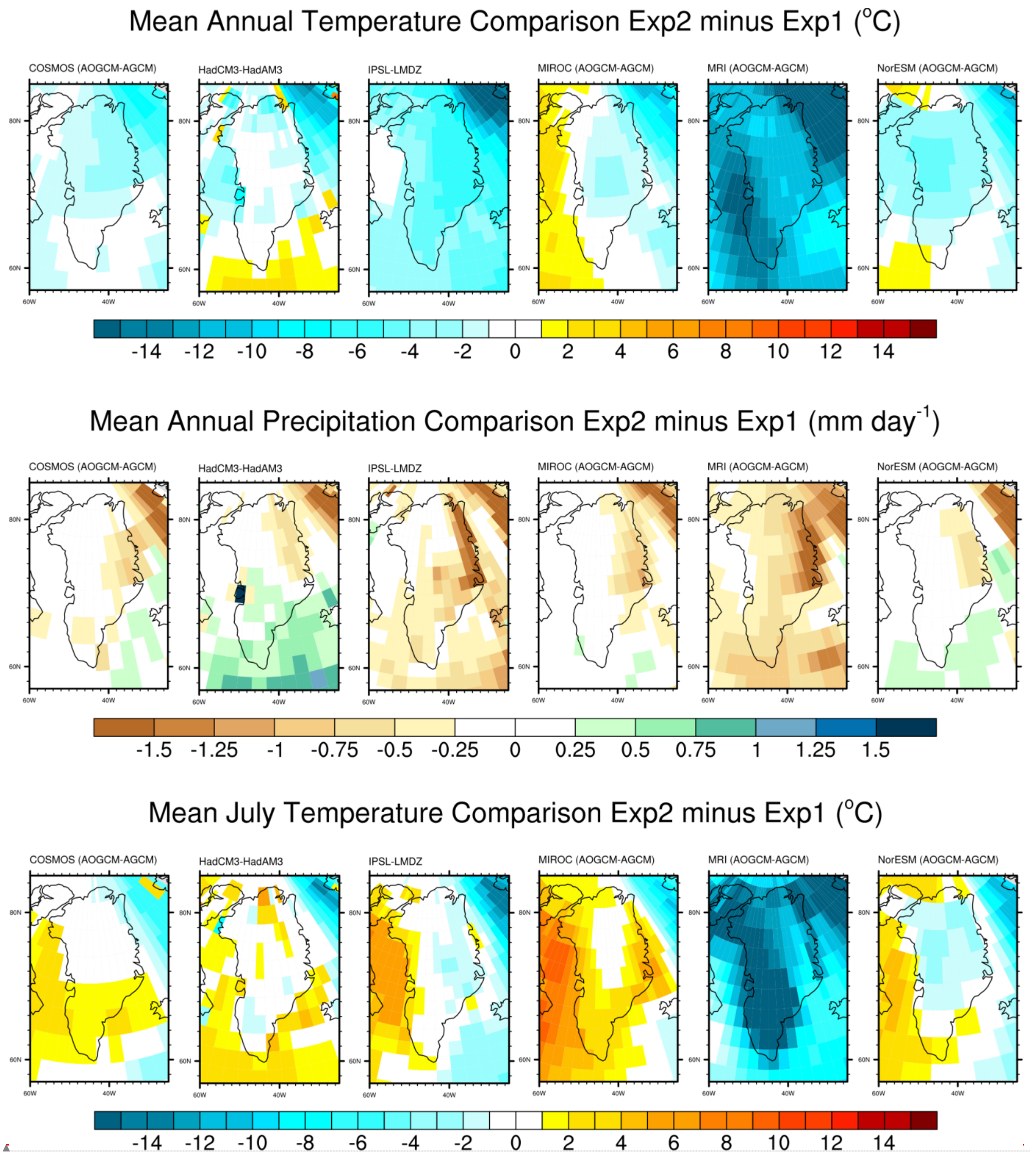


Figure 11: Mid-Pliocene annual mean clear sky albedo values over Greenland for PlioMIP models (where available).



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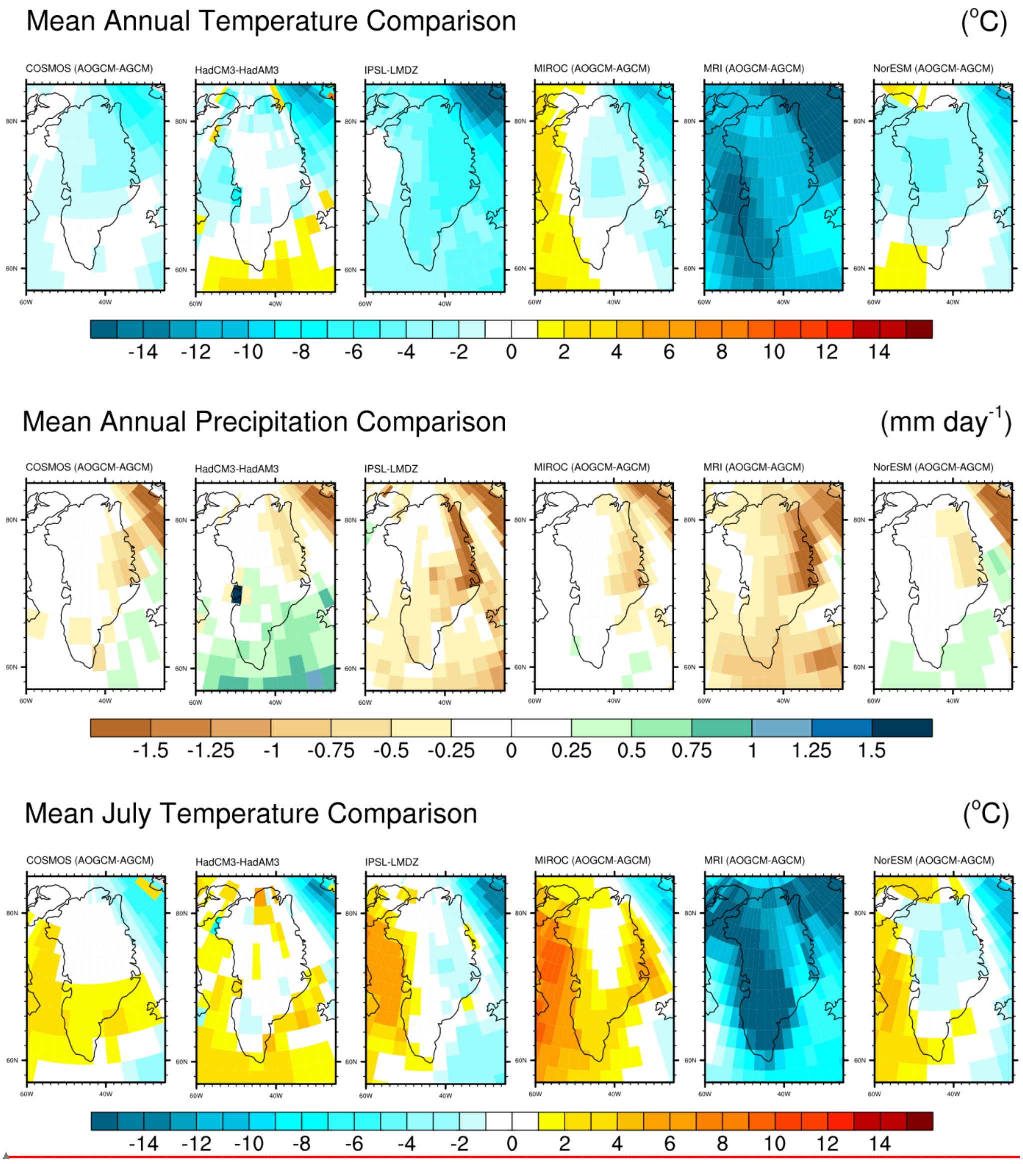

Figure 12: Pliocene mean annual temperature (°C) and precipitation (mm day^{-1}), and mean July temperature differences simulated between the AOGCMs and Experiment 2 and Experiment 1AGCMs over Greenland for comparable models from the PlioMIP ensemble (AOGCM climate minus AGCM climate).

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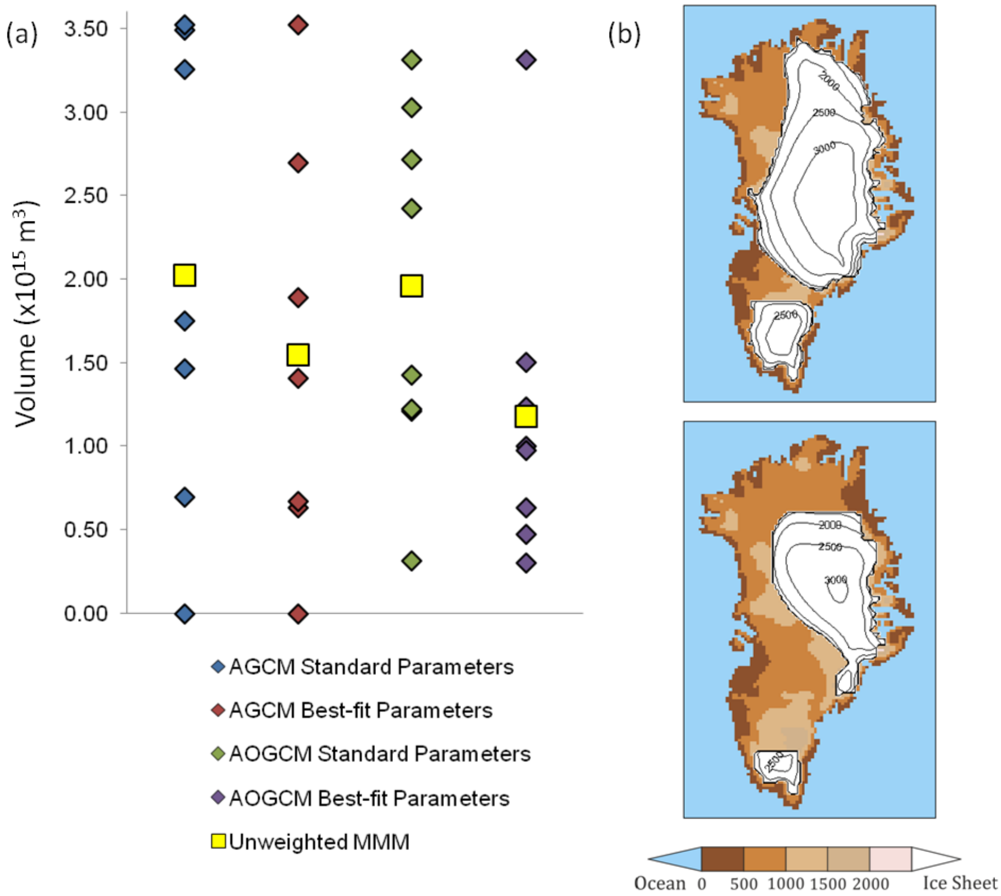

Figure 13: (a) Summary of the spread of mid-Pliocene GrIS volumes for each model within the PlioMIP ensemble (AGCM and AOGCM) compared with the un-weighted MMM for either the standard BASISM glaciological parameter set or for the parameter set that gives the 'best' volumetric representation of the modern GrIS. (b) Ice sheet configuration with the closest volume equating to the largest (top) and smallest (bottom) MMM volume.

Supplementary Information: **Using results from the PlioMIP ensemble to investigate the Greenland Ice Sheet during the warm Pliocene**

Supplementary Table 1: GrIS diagnostics for the PlioMIP simulations, including volume and ice area using the different parameter sets described as shown by the coloured circles in Figures 5 and 7. Values are given as a difference from the simulated pre-industrial GrIS, when the same GCM pre-industrial forcing climatology is used. For example, negative volume or area means that the GrIS reduces in size compared to the GCM pre-industrial control.

	Model Name	Standard parameter set used within BASISM (Red circles) Volume ($\times 10^6$ km^3)	Parameter set that gives a volumetric reconstruction closest to observed (Blue circles) Volume ($\times 10^6$ km^3)	Parameter set that gives the lowest RMSE in terms of thickness (Yellow circles) Volume ($\times 10^6$ km^3)
AGCMs	CAM3.1	-2.70	-2.83	-2.84
	COSMOS	0.14	-0.65	-0.27
	HadAM3	-1.27	-1.53	-1.28
	LMDZ5A	-1.67	-2.42	-2.42
	MIROC4m	0.19	-1.36	-1.36
	MRI-CGCM2.3	0.22	0.41	0.41
	NorESM-L	-3.46	-3.43	-3.43
AOGCMs	CCSM4	-0.27	-0.53	-0.88
	COSMOS	-0.66	-2.14	-2.14
	GISS ModelE2-R	-1.89	-2.62	-2.62
	HadCM3	-1.73	-2.15	-2.15
	IPSLCM5A	-1.85	-2.36	-2.01
	MIROC4m	-0.83	-2.46	-2.46
	MRI-CGCM2.3	0.20	0.20	0.20
	NorESM-L	-3.12	-3.13	-3.18