Tokyo, Japan, Monday 5th October

Dear Dr. Didier Roche, Editor of the Geoscience Model Development,

We thank you and the reviewers for the devoted time and efforts for this submitted manuscript, GMD-2015-80.
We responded to all the comments of both reviewers point by point in blue and the change in the text is incorporated as in red for each comment. Also the manuscript with the change is marked to see how the change was incorporated.
We hope that with these changes the manuscript can now be accepted for publication in the Geoscience Model Development.

Best regards,
Ayako Abe-Ouchi
Fuyuki Saito, Masa Kageyama, Pascale Braconnot, Sandy P. Harrison, Kurt Lambeck, Bette L. Otto-Bliesner, Dick Peltier, Lev Tarasov, Jean-Y Peterschmitt and Kunio Takahashi

Reply to reviewer #1

(1-1) However, I see a problem when the authors compare PMIP2 and PMIP3 modeling results. These are very different models and even if the same ice sheets reconstruction would be used in PMIP2 and PMIP3, significant differences between global SAT anomalies averaged over the different models ensemble are unavoidable.
Even more, because radiative forcing of ice sheet depends not only on prescribed ice sheets but also on models (for PMIP3 this difference is more than 30% across the model ensemble), differences in global mean radiative forcing of ice sheets cannot be solely attributed to differences in ice sheet reconstructions used in PMIP2 and PMIP3. Therefore the authors cannot claim that simulated difference in radiative forcing of ice sheets, elevation and land area between PMIP3 and PMIP 2 of 1 W/m2 is caused by difference in ice sheet reconstruction. Similarly 0.5C extra cooling in PMIP3 ensemble cannot be attributed to different ice sheet reconstructions. Obviously, I do not suggest redoing PMIP3 ensemble with PMIP2 ice sheets reconstruction but such experiment can be perform in principle with the AGCM-slab ocean model. In any case, this potential caveats should be discussed in the manuscript.
We agree that the difference between PMIP2 and PMIP3 is not only due to the change of ice sheet configuration but could also be influenced by changes in model version, and we have made this caveat clearer in the revised text. However, we would like to clarify that the conclusion is not simply based on comparing the ensemble mean between PMIP2 and PMIP3 simulations, but by comparing results for different models. Three models have run simulations with both the PMIP2 and CMIP5/PMIP3 ice sheets, and these give similar estimates of the difference in radiative forcing due to replacing the PMIP2 ice sheet with the CMIP5/PMIP3 ice sheet as obtained from the ensemble mean. Even though there is a change in model version between PMIP2 and PMIP3, the LGM forcing and temperature change (LGM-PreIndustrial) is always larger in PMIP3 than in PMIP2 simulations. This systematic behaviour would be unlikely to occur if

it was solely due to changes in model configuration (some models would show larger and other smaller estimates), which is why we can state with some confidence that this is due to the ice sheet. In addition a simple estimate of the impact of the different ice-sheet on the radiative forcing is provided in Braconnot et al. (2012, Nature Climate Change) and leads to the conclusion that the forcing would be larger with PMIP3 than with PMIP2 ice-sheet. This point is treated in more depth in Braconnot and Kageyama, (Phil. TransA, in press).
We have made changes to the manuscript to clarify these various points; these are detailed under our response to the specific comment (1-19) below.

(1-2) Some parts of the manuscripts, especially introduction, require improvements of the style. In particular, several sentences (like that on page 4298, lines 2-9) are lengthy and difficult for understanding.
We have now revised the text substantially to deal with specific comments, and in doing so have paid special attention to ensuring clarity. We agree that the text identified on page 4298, lines 2-9) was especially opaque and have revised this as follows:
Ice-sheet height has major impacts on surface temperature via lapse rate, planetary-scale atmospheric circulation and the location of storm tracks, and hence precipitation patterns, and even on ocean circulation. Simulations using different ice sheet configurations have demonstrated these large differences both in global mean temperature and in NH circulation patterns and regional temperatures (Justino et al., 2005; Otto-Bliesner et al., 2006; Abe-Ouchi et al., 2007; Clark et al., 2009; Pausata et al., 2011; Vettoretti and Peltier, 2013; Ullman et al., 2014; Zhang et al., 2014).

(1-3) I would also suggest to use more precise scientific terminology. In particular, sheet reconstructions are not “boundary conditions”, at least, in mathematical or physical sense.
The term “boundary condition” is generally used in the climate modeling community to mean something that affects climate but is not explicitly simulated. We agree that this is not the strict mathematical definition of the term, and we have therefore added a sentence at the beginning of the second paragraph of the introduction to make it clear what we mean by this as follows:
Factors affecting climate that are not simulated explicitly, usually designated boundary conditions, need to be specified in both control and palaeoclimate model simulations.

We have also modified the abstract to replace this term:
We describe the creation of a data set describing changes related to the presence of ice sheets ....

(1-4) Another example is “shallow ice-sheet model”. This is rather rear and confusing term. I would suggest using the standard term – ice sheet model based on shallow ice approximation.
We have modified this to read:
The GSM incorporates a 3-D thermo-mechanically coupled ice-sheet model based on the shallow ice approximation, ...

Specific comments
(1-5) p. 4295, l. 2. “: : : the creation of boundary conditions: : :” See my general comments.
This has been modified to:
We describe the creation of a data set describing changes related to the presence of ice sheets ....

(1-6) p. 4295, l. 10. "albedo mask" sounds strange. Do you mean ice sheet mask?
We were trying to convey the idea that the albedo values specified in the model for both ice-covered and ice-free land are determined by ice sheet extent rather than ice-sheet elevation. However, since the albedo of ice-free land is not discussed subsequently in the paper, we feel that this sentence can be simplified to:
The ice sheet extent in the Northern Hemisphere (NH) does not vary substantially between the three individual data sources.

(1-7) p. 4295, l. 22. "There are much larger differences in the climate response to the latest reconstructions: : :" The meaning is not clear.
We agree that this was not very clear. We have simplified the last two sentences of the abstract to clarify our meaning as follows:
Differences between the climate response to the CMIP5/PMIP3 composite and any individual ice-sheet reconstruction are smaller than those between the CMIP5/PMIP3 composite and the ice sheet used in the last phase of PMIP (PMIP2).

(1-8) p. 4296, l 5. I cannot see how PMIP type experiment can help in understanding of the causes of uncertainties in future climate predictions.
Palaeoclimate experiments such as those run by PMIP provide an opportunity to evaluate how well models used for future projections simulate large climate changes; these kinds of comparisons also allow us to identify the causes of differences between models and hence can help to identify potential sources of the differences in the 21st century projections. They help improve understanding of the potential causes of uncertainties in future climate both by identifying systematic biases in model response to forcing, and in determining whether these biases are related to specific model processes or feedbacks. We agree that our statement was too condensed to make the direct contribution to projections clear and so we have rewritten this text as follows:
Modelling of past climate states, and evaluation of the simulations using paleoclimate reconstructions, provide unique opportunities to assess the performance of models used for future climate projections when subjected to large changes in forcing (Braconnot et al., 2012; Masson-Delmotte et al., 2013; Schmidt et al., 2014; Harrison et al., 2015). Palaeo-evaluations are also useful in identifying the causes of inter-model differences in simulated climate responses (Schmidt et al., 2014; Harrison et al., 2015). Thus, the simulation of past climates provides an opportunity to identify and quantify systematic biases that are likely to be present in future climate projections and to explore the potential causes of inter-model spread in these projections.

(1-9) P. 4296, l 8. Please remove "change".
We mean the change in forcing compared to today. We have expanded the text to clarify this as follows:
The Last Glacial Maximum (LGM, ca. 21 000 yr BP) is an exemplary period for such an exercise because the change in global forcing (relative to the present) was large and, although the forcing was different in nature, similar in magnitude to that expected by the end of the 21st century (Braconnot et al., 2012).

(1-10) p. 4297, l. 12. I would suggest to use "ice sheet topography" instead of "overall form of the ice sheet".
We have changed this to ice-sheet topography, as suggested.

(1-11) p. 4297, l. 29. “the change in land-sea geography has impacts on sea level: : :” I suppose that it is other way around, namely, sea level affects land/sea distribution.
Yes, the primary direction of causality is that ice sheet changes affect sea level and hence land-sea geography. The key point here is that the change in land-sea geography then has impacts on ocean circulation. We have rewritten this sentence as:
Furthermore, the change in ice sheets affects the carbon cycle and atmospheric CO2 concentrations in glacial cycles (Brovkin et al., 2012; Ganopolski and Calov, 2011; Abe-Ouchi et al., 2013).

(1-12) p. 4301, l. 12 What is EOFS?
We have defined the abbreviation as :
Empirical Orthogonal Functions (EOFs)

(1-13) p. 4301, l. 23. What is “margin forcing”?
This is the terminology defined and used originally in the Tarasov and Peltier papers (see e.g. section 2.4 in the Tarasov and Peltier (2004). We would like to keep the term, but have provided an explanation of its meaning as follows:
Model runs are penalised in proportion to the amount of margin correction (or “margin forcing”, see section 2.4 of Tarasov and Peltier, 2004) required, ...

(1-14) p. 4307. In the left hand side of the Eq. 10 should be “Mask_1,ave”
Thanks for this correction, which we have now implemented as:
Mask_1,ave

(1-15) p. 4307, l. 15. The meaning of “masked surface altitude” is not clear to me.
We have revised this to make the meaning clearer to:
is the surface elevation field extended over undefined gridpoints such that ...

(1-16) p. 4308. L. 10. “The ANU reconstruction consistently shows the largest changes: : :” Do you mean that the ice volume of ALL ice sheets in ANU reconstruction are larger than in the other two?
This is in fact correct: all of the individual ANU ice sheets are larger than these ice sheets in the other two reconstructions. We have revised the text to make this clear as:
The ANU reconstruction shows larger changes in all of the individual ice sheets than shown by either the GLAC-1a or the ICE-6G v.2 reconstruction, while the GLAC-1a reconstruction shows smaller changes in NH ice sheet volume than the other two reconstructions

(1-17) p. 4310, l. 12. Why “but”? I would say “and” instead
The point here was to contrast the ANU reconstruction and the other two reconstructions: although all of the reconstructions show two domes, ANU has a higher western than eastern dome while the other reconstructions have two broadly equal height domes. We have rewritten this sentence to make it clearer as follows:
The ANU reconstruction has elevations > 3000m for the western dome, whereas both domes are of similar and lower (2000–3000m) elevations in the ICE-6G v.2 and GLAC-1a reconstructions (Figures 1, 2).

(1-18) p. 4311, l.5. Please remove “change”.
The use of the word change is correct because we mean the difference between the LGM and control forcing. Since it was perhaps unclear what was meant here, we have modified the sentence to read:
According to these calculations, the forcing resulting from the change in the ice-sheet alone is between -1.85 and -3.49Wm-2 depending on the climate model (Table 3), while the total change in forcing resulting from the imposition of LGM boundary conditions varies between -3.62 and -5.20Wm-2.

(1-19) p. 4311. L. 5. Please make it clear (see my general comment) that the difference of 1 W/m2 is caused not only by different ice sheet reconstructions but also because of using of different climate models.
As we have pointed out above, this estimate of the impact of the ice sheet is reasonable. There are indeed differences in model configuration that influence this difference, but the conclusion is not simply based on comparing the ensemble of models (where the difference is indeed a conflation of both model version changes and ice sheets changes between PMIP2 and CMIP5/PMIP3). Examination of the three individual models shows that were included in the PMIP2 and CMIP5/PMIP3 show that the change in radiative forcing is always greater in the CMIP5/PMIP3 experiments (and the difference is of a similar magnitude, ca 1 W/m2) – which would be unlikely to be the case if it was due to differences in model versions. We have added a paragraph to the end of section 4.3 to make these arguments clearer as follows:
Technically, the estimated difference in forcing between the PMIP2 and CMIP5/PMIP3 simulations obtained through these analyses reflects both differences in the ice sheet reconstruction (other boundary conditions are the same in the two sets of experiments) and differences in the version of the model used for the PMIP2 and CMIP5/PMIP3 experiments. Only three modeling groups (CCSM, IPSL, MIROC) have made LGM simulations in using both the PMIP2 and CMIP5/PMIP3 ice sheets. They show an average change in total forcing of 1.34Wm-2 with the change in radiative forcing caused by the ice sheet is ca 1Wm-2, i.e. of comparable magnitude to the estimate obtained from the ensemble mean. The impact of changes in individual model configuration would be unlikely to yield the systematic increase in forcing between PMIP2 and CMIP5/PMIP3 shown by these three models. Thus, it seems plausible that the estimate of the effect of using the CMIP5/PMIP3 ice sheet obtained by comparing the PMIP2 and CMIP5/PMIP3 ensemble of simulations is realistic.
We have also added text in our discussion of the change in radiative forcing as follows:
These estimates are derived from the ensemble of simulations made for each set of experiments, and thus we cannot exclude a contribution from changes in model configuration to the apparent difference in forcing and temperature response between the PMIP2 and CMIP5/PMIP3 results. However, the three models from the ensemble which performed both sets of experiments all show an estimate of a difference in forcing due to ice sheet configuration of ca 1.0Wm-2, which suggests that this is a result of a systematic difference in the simulation protocol rather than the non-systematic changes that might be expected to result from changes in model configuration. While it would clearly be useful for a larger number of modeling groups to test the impact of ice sheet configuration, it seems plausible that the use of the CMIP5/PMIP3 ice sheet results in an increase of radiative forcing of ca 1.0Wm-2 compared to the previous generation of PMIP simulations.

(1-20) p. 4312, l. 3. “increase in global mean annual temperature of ca 0.5 C compared to the PMIP2 experiments”. In fact, according to the Table 3, global SAT is lower in the PMIP3 compare to PMIP2.
We agree that the wording here was confusing and have revised the text to read:

the use of the CMIP5/PMIP3 composite ice sheet produces an additional reduction of ca 0.5 °C in global mean annual temperature compared to the PMIP2 experiments

(1-21) p. 4312, l. 6. What is “ideal world” and how it is related to ice sheet reconstructions?
We agree that this was a somewhat fanciful way of stating the point that there is as yet no perfect consensus about the form of the LGM ice sheets, and that this was our justification for constructing a composite ice sheet. We have rewritten this paragraph as follows:

(1-22) p. 4312, l.18. “implied” or prescribed?
This should be prescribed and has been changed accordingly.

(1-23) p. 4312, l. 23.Because different models participated in PMIP2 and 3, it should be “difference in global mean annual temperature ANOMALIES is 0.5C”
We have rewritten this as:
the average (ensemble) difference in the global mean annual temperature anomaly is ca 0.5°C.

(1-24) p. 4313, l. 20-22. This is a questionable argument. Two Antarctic reconstructions used for PMIP3 are so different that at least one of them should be wrong.
We agree that there are substantial differences between the two Antarctic reconstructions used to form the composite, and that therefore at least one of them is wrong. We are not arguing that either is correct in this paragraph.The fact that the composite ice sheet produces a reasonable simulation of Antarctic cooling suggests that both of them are wrong, and that the compromise composite is closer to reality. We cannot dismiss the possibility that model improvements have led to the improvement in the simulation of Antarctic temperatures, but given that changes to the models between PMIP2 and PMIP3 vary between models, it seems more likely that the change in boundary conditions has a systematic influence on the simulations. This is why we stress the fact that the correct simulation of Antarctic cooling is unlikely if the composite ice sheet was substantially wrong, while acknowledging the fact that this improvement may also be related to changes in the models. We have therefore left this comment unchanged.

(1-25) p. 4313, l. 23 What is “observation margin”?
This was a typographic error and should have been observed margin. This has now been corrected.

(1-26) Table 1. The longitudinal range for GLAC-1a (347.25, 479.25) is odd. Please change to (-12.75, 119.25).
Thanks for spotting this; we have now corrected the table.

(1-27) Fig. 6 caption. “difference in radiative forcing and feedbacks” sounds strange to me. How the difference between feedbacks is measured? Please also specify the units.
This has been revised to “difference in radiative forcing (in W/m^2)”

(1-28) Fig. 7 Panel (a) does not show “MAT in the simulation with the CMIP5/PMIP3 composite ice sheet“. It definitely shows differences between PMIP2 and PMIP3 but the meaning of “MIROCs” is unclear.
We apologise for the mismatch between the caption and the figure. We have now provided a new caption for Figure 7 as follows:

Figure 7. Differences in mean annual temperature (˚C) caused by using different ice sheet configurations from the CMIP5/PMIP3 composite ice sheet in simulations made with the MIROC slab ocean model. The individual ice sheet configurations are (a) PMIP2, (b) ICE-6Gv.2, (c) GLAC-1a, and (d) ANU ice sheets, where each is referenced to the CMIP5/PMIP3 composite ice sheet. The land mask (> 50 % land) is shown in grey, the ice margin (> 50 % ice) is shown in black on all four plots.

(1-29) Fig. 8 "where the temperature is higher than -9C" I suppose it should be "where temperature anomalies is smaller than -9C".
We agree that the caption was not clear and have revised this as follows:
Figure 8. Change in mean annual temperature (˚C) in the (a) PMIP2 and (b) CMIP/5PMIP3 coupled ocean-atmosphere simulations. Each of these plots is an ensemble average of all the LGM simulations in PMIP2 and CMIP5/PMIP3 respectively. The difference between the ensemble mean results for the two generations of experiments is shown in plot (c). The land mask (> 50 % land) is shown in grey, the ice margin (> 50 % ice) is shown in black on all plots. Contour lines in (a) and (b) are at 1˚C intervals to −9˚C; temperature differences > −9˚C are not differentiated.

Reply to reviewer #2

(2-1) My main criticism is that, in some places, the paper reads as if its main intention were to be a guide for dealing with the presence of ice sheets in further CMIP5/PMIP3 experiments. For instance, the very first sentence in the abstract: "We describe the creation of boundary conditions ... for use in LGM experiments ... as part of ... CMIP5 and …PMIP3". However, with the publication of the IPCC AR5 in 2013/2014, CMIP5/PMIP3 is essentially history, and the community is now heading towards CMIP6 (including a further stage of PMIP). So I suggest to be more outspoken on this point, change the manuscript accordingly and, in section 5 (Discussion and conclusions), discuss in some more detail the perspectives for future work.
The blended ice sheet was created for use in the CMIP5/PMIP3 simulations. Our purpose here is to document the construction of this ice sheet, not as a background to new experiments but rather as a background to ongoing analyses of these simulations. We do not agree with the reviewer that the CMIP5/PMIP3 simulations are essentially history. There are only a relatively few published papers comparing model responses at the LGM, and there is still a lot to be learnt – not least about the response to ice-sheet configuration – from these ongoing analyses of the CMIP5/PMIP3 simulations. The reviewer is correct to say that we are moving towards a new phase of CMIP (CMIP6/PMIP4); while the results from the CMIP5/PMIP3 experiments will inform the choice of ice sheet for the new simulations, the decision about the CMIP6/PMIP4 ice sheets will be made and documented (in a GMD paper associated with the CMIP special issue) independently. We therefore do not think it appropriate to discuss the choice of the CMIP5/PMIP4 ice sheet in this paper.
While we clearly state the purpose of our paper in the introduction, we agree that the tense used in the abstract could be read to suggest that there will be new simulations, and we have therefore modified this sentence to read:
We describe the creation of a data set describing changes related to the presence of ice sheets, including ice sheet extent and height, ice shelf extent, and the distribution and elevation of ice-free land, at the Last Glacial

Maximum (LGM) that were used in LGM experiments conducted as part of the fifth phase of the Coupled Modelling Intercomparison Project (CMIP5) and the third phase of the Palaeoclimate Modelling Intercomparison Project (PMIP3).

Given that we end the paper with a brief discussion of developments that will affect future prescription of ice-sheets for modelling , we agree with the reviewer that it is worth adding something about the CMIP6/PMIP4 simulations. Since we are not in a position to discuss the protocol that will be adopted for the CMIP6/PMIP4 simulations, we have modified the final paragraph to read:
Our knowledge of the LGM ice-sheet/ice-shelf reconstruction is continually improving, as are the models that are used to reconstruct the most likely distribution of ice mass (Whitehouse et al., 2012; Anderson et al., 2014; Bentley et al., 2014; Mackintosh et al., 2014; Briggs et al., 2014; Lambeck et al., 2014; Peltier et al., 2015; Hall et al., 2015). Indeed, there have been updated reconstructions of LGM ice sheet configuration since the CMIP5/PMIP3 ice sheet was constructed. For example, the ICE-6G_C (VM5a) reconstruction is an updated version of the ICE-6G(VM5a) v2.0 model discussed here, and informed by a much richer data base of space geodetic information (Argus et al., 2014; Peltier et al., 2015). It is inevitable that there will be further changes in the future, although less clear when there will be a consensus about their form. It is imperative, then, that a wider range of models conduct sensitivity tests to the impact of ice sheet configuration, focusing on both near-field and remote impacts on climate. This would make it possible to draw on the wealth of palaeoclimate data from beyond the ice sheets to evaluate, and perhaps even constrain, ice-sheet reconstructions.

Minor issues:
(2-2) "Eurasian Ice Sheet" vs. "Eurasian ice sheet" etc.: Both forms are OK (with a slightly different touch). However, capitalisation or non-capitalisation should be done uniformly.
We have corrected this throughout the manuscript to Eurasian ice sheet.

(2-3) I suggest to replace "altitude" by "elevation" throughout the manuscript. Altitude is more commonly used for heights above some reference for points or objects _above_the ground (e.g., airplanes), while elevation is the preferred term for heights above sea level of locations _on_ the ground (e.g., the surface of an ice sheet).
We have replaced altitude by elevation throughout the manuscript.

(2-4) Page 4313, line 23: "observation margin" -> "observed margin".
We have corrected this to observed margin.

(2-5) Page 4314, line 21: "Jun’ici" -> "Jun’ichi" (I suppose).
Thank you for pointing out this typo, which we have now corrected.

(2-6) Table 1: The notation for the latitude and longitude intervals is strange. Rather add square brackets, e.g., "-89.5, 89.5" -> "[-89.5, 89.5]". Further, the units are missing for all latitudes and longitudes.
We have added square brackets for the latitude and longitude intervals, and have taken the opportunity to correct the intervals for the Eurasian ice sheet as covered by GLAC-1. We have modified the caption to

describe the convention used for latitude and longitude. We have added units for latitude and longitude, and also added units for resolution since these are also all in degrees.

(2-7) Table 2: "Implied changes" -> "Implied changes (LGM - present)".
We have changed this to:
Implied changes (Last Glacial Maximum – present)

(2-8) p. 4312, l.18. “implied” or prescribed?
We have revised this to prescribed

(2-9) Table 3: In all three "change" columns, the units are missing. As for the last column (resulting change in temperature Delta_tas), exactly what temperature is that? BTW, "tas" is a strange symbol for temperature.
We have modified the caption to clarify the units and to change the terminology for global mean surface temperature. We have also added the units to the table itself. The caption now reads:

Change in radiative forcing (W m^{-2}) associated with changes in ice sheet and implied changes in land-sea geography, calculated for the CMIP5/PMIP3 composite and the PMIP2 ice sheets respectively. The resulting change in global annual mean surface air temperature ($^{\circ}$C) is shown in the last column. The error is calculated as the difference between the estimates obtained while using the present day climate as a reference or the glacial climate as a reference in the partial-radiative perturbation calculation. Note that the values given for the PMIP2 ice sheet are slightly different from those given in Braconnot et al. (2012) because of corrections made subsequent to the publication of that paper. Values given here may also differ slightly from published results of individual models where either a different method or a different time window was used for the calculation.

(2-10) Figures 6-9: Units missing.
We have revised the captions for Figure 6 through 9, to clarify the units and to improve the explanation. The captions now read:
Figure 6. Estimation of the difference in radiative forcing (W m^{-2}) at the LGM compared with pre-industrial conditions caused by imposition of the CMIP5/PMIP3 ice sheet and the change in the land-sea mask. The map is a composite of the results from five ocean–atmosphere models showing the spatial patterns of the change in total forcing associated with the expanded Northern Hemisphere ice sheets at the LGM and with the increase of land area due to lowered sea level.

Figure 7. Differences in mean annual temperature ($^{\circ}$C) caused by using different ice sheet configurations from the CMIP5/PMIP3 composite ice sheet in simulations made with the MIROC slab ocean model. The individual ice sheet configurations are (a) PMIP2, (b) ICE-6Gv.2, (c) GLAC-1a, and (d) ANU ice sheets, where each is referenced to the CMIP5/PMIP3 composite ice sheet. The land mask (> 50 % land) is shown in grey, the ice margin (> 50 % ice) is shown in black on all four plots

Figure 8. Change in mean annual temperature ($^{\circ}$C) in the (a) PMIP2 and (b) CMIP/5PMIP3 coupled ocean-atmosphere simulations. Each of these plots is an ensemble average of all the LGM simulations in PMIP2 and CMIP5/PMIP3 respectively. The difference between the ensemble mean results for the two

generations of experiments is shown in plot (c). The land mask (> 50 % land) is shown in grey, the ice margin (> 50 % ice) is shown in black on all plots. Contour lines in (a) and (b) are at 1° C intervals to -9°C; temperature differences > -9°C are not differentiated.

Figure 9. Implementation of the CMIP5/PMIP3 composite ice sheet in individual models. The plots show the surface elevation (m) as implemented in each model, and thus reveal that there are small differences in prescribed ice sheet between models because of differences in e.g. model type and resolution.

Manuscript prepared for Geosci. Model Dev.
with version 2014/09/16 7.15 Copernicus papers of the LaTeX class copernicus.cls.
Date: 28 October 2015

Ice-sheet configuration in the CMIP5/PMIP3 Last Glacial Maximum experiments

A. Abe-Ouchi[1,2], F. Saito[2], M. Kageyama[3], P. Braconnot[3], S. P. Harrison[4], K. Lambeck[5], B. L. Otto-Bliesner[6], W. R. Peltier[7], L. Tarasov[8], J.-Y. Peterschmitt[3], and K. Takahashi[2]

[1]Atmosphere Ocean Research Institute, University of Tokyo, 5-1-5, Kashiwanoha, Kashiwa-shi, Chiba 277-8564, Japan
[2]Japan Agency for Marine-Earth Science and Technology, 3173-25 Showamachi, Kanazawa, Yokohama, Kanagawa, 236-0001, Japan
[3]Laboratoire des Sciences du Climat et de l'Environnement/Institut Pierre Simon Laplace unité mixte de recherches CEA-CNRS-UVSQ, Orme des Merisiers, point courrier 129, 91191 Gif sur Yvette Cedex, France
[4]Centre for Past Climate Change and School of Archaeology, Geography and Environmental Sciences, University of Reading, Whiteknights, Reading, RG6 6AH, UK
[5]Research School of Earth Sciences, The Australian National University, Canberra, ACT 0200, Australia
[6]Climate and Global Dynamics Division, National Center for Atmospheric Research, Boulder, CO 80305, USA
[7]Department of Physics, University of Toronto, 60 George Street, Toronto, Ontario, M5S 1A7, Canada
[8]Department of Physics and Physical Oceanography, Memorial University of Newfoundland, St. John's, NL A1B 3X7, Canada

Correspondence to: A. Abe-Ouchi (abeouchi@aori.u-tokyo.ac.jp)

Abstract. We describe the creation of a data set describing changes~~boundary conditions~~ related to the presence of ice sheets, including ice sheet extent and height, ice shelf extent, and the distribution and elevation~~altitude~~ of ice-free land, at the Last Glacial Maximum (LGM) that were used~~for use~~ in LGM experiments conducted as part of the fifth phase of the Coupled Modelling Intercomparison Project (CMIP5) and the third phase of the Palaeoclimate Modelling Intercomparison Project (PMIP3). The CMIP5/PMIP3 data sets were created from reconstructions made by three different groups, which were all obtained using a model-inversion approach but differ in the assumptions used in the modelling and in the type of data used as constraints. The ice sheet extent in~~, and thus the albedo mask, for~~ the Northern Hemisphere (NH) does not vary substantially between the three individual data sources. The difference in the topography of the NH ice sheets is also moderate, and smaller than the differences between these reconstructions (and the resultant composite reconstruction) and ice-sheet reconstructions used in previous generations of PMIP. Only two of the individual reconstructions provide information for Antarctica. The discrepancy between these two reconstructions is larger than the difference for the NH ice sheets although still less than the difference between the composite reconstruction and previous PMIP ice-sheet reconstructions. Although largely confined to the ice-covered regions, differences between the climate response to the individual LGM reconstructions extend over North Atlantic Ocean and Northern Hemisphere continents, partly through atmospheric stationary waves. Differences between the climate response to the CMIP5/PMIP3 composite and any individual ice-sheet reconstruction are smaller than those between the CMIP5/PMIP3 composite and the ice sheet used in the last phase of PMIP (PMIP2).~~Differences in the climate response to the individual LGM reconstructions, and between these reconstructions and the CMIP5/PMIP3 composite, are largely confined to the ice-covered regions.There are much larger differences in the climate response to the latest reconstructions (or the derived composite) and ice-sheet reconstructions used in previous phases of PMIP.~~

1 Introduction

There are large differences in the modelled response to scenarios of future climate forcing (Kirtman et al., 2013; Collins et al., 2013). Modelling of past climate states, and evaluation of the simulations using paleoclimate reconstructions, provide unique opportunities to assess the performance of models used for future climate projections when subjected to large changes in forcing (Braconnot et al., 2012; Masson-Delmotte et al., 2013; Schmidt et al., 2014; Harrison et al., 2015). Palaeo-evaluations are also useful in identifying the causes of inter-model differences in simulated climate responses (Schmidt et al., 2014; Harrison et al., 2015). Thus, the simulation of past climates provides an opportunity to identify and quantify systematic biases that are likely to be present in future climate projections and to explore the potential causes of inter-model spread in these projections.~~Modelling of past climate states, and evaluation of the simulations using~~

~~palaeoclimate reconstructions, provides an opportunity to quantify and to explore the causes of these uncertainties (Braconnot et al., 2012, Masson-Delmotte et al., 2013, Schmidt et al., 2014).~~ The Last Glacial Maximum (LGM, ca. 21 000 yr BP) is an exemplary period for such an exercise because the change in global forcing (relative to the present) was large and, although the forcing was different in nature, similar in magnitude to that expected by the end of the 21st century (Braconnot et al., 2012). ~~The Last Glacial Maximum (LGM, ca. 21 000 yr BP) is an exemplary period for such an exercise because the change in global forcing was large and, although the forcing was different in nature, the magnitude is equivalent to that expected by the end of the 21st century (Braconnot et al., 2012).~~ The LGM has been a major focus for simulations since the early days of numerical modelling (e.g. Alyea, 1972; Williams et al., 1974; Gates, 1976; Manabe and Hahn, 1977; Kutzbach and Guetter, 1986). It~~, and~~ was chosen as a focus for model experiments ~~carried out~~ in both Phase 1 and Phase 2 of the Palaeoclimate Modelling Intercomparison Project (PMIP: Braconnot et al., 2007a, b) because of the availability of syntheses of palaeoclimatic reconstructions (e.g. MARGO Project Members, 2009; Bartlein et al., 2011; Schmittner et al., 2011; Braconnot et al., 2012) for model evaluation. It is perhaps not surprising then that the LGM was one of the simulations chosen when palaeoclimate experiments were first included in the fifth phase of the Coupled Modelling Intercomparison Project (CMIP5: Taylor et al., 2012; Braconnot et al., 2012~~Taylor 2011 Braconnot 2012~~). The LGM simulations are further examined to constrain the climate sensitivity, which is an important metrics for the future climate projection (Masson-Delmotte et al., 2006, 2013; Hargreaves et al., 2007; Yoshimori et al., 2009, 2011; Brady et al., 2013).

Factors affecting climate that are not simulated explicitly, usually designated boundary conditions, need to be specified in both control and palaeoclimate model simulations. The boundary conditions that must be specified for the LGM experiment are a (relatively small) change in orbital forcing, reduced atmospheric concentrations of greenhouse gases, and the presence of large ice sheets. Land-surface conditions, in particular the distribution of vegetation (Prentice et al., 2000; Harrison and Bartlein, 2012), were also different at the LGM. On the other hand~~However~~, the spatial coverage of information on LGM vegetation is currently insufficient to provide a gridded global data set to use as a model input. LGM vegetation was therefore either computed by the model or prescribed to be the same as the pre-industrial control simulation. However, the changes in orbital forcing and greenhouse gas concentrations are well known. The expansion of the ice sheets at the LGM resulted in a sea-level lowering of ca 130 m and changed palaeogeography. The marginal limits of the North American (Laurentide), Greenland and European ice sheets are increasingly well constrained by radiocarbon dated moraines and other glacial deposits (e.g. Dyke and Prest, 1987; Mickelson and Colgan, 2003; Dyke, 2004; Gyllencreutz et al., 2007; Simpson et al., 2009; Ehlers et al., 2011; Mangerud et al., 2013). However, there is little direct evidence for the distribution of ice mass, and this must therefore be inferred through a combination of physical modelling and the use of indirect observational constraints (such as information on relative sea level changes). Thus, the specification of ~~the overall form of the~~ ice-sheet topography~~ice sheets~~ has been a major source of uncertainty in defining boundary conditions for LGM experiments.

The earliest LGM simulations made use of a reconstruction of ice sheet extent and height made by the CLIMAP project (CLIMAP Project Members, 1976; CLIMAP, 1981). Subsequently, the PMIP project made use of reconstructions based on two different generations of an isostatic rebound model: ICE-4G (Peltier, 1994) in the first phase of the project (PMIP1) and ICE-5G v1.1 in PMIP2 (Peltier, 2004). The inferred ice volume was ca 35 % lower in ICE-4G than in the earlier CLIMAP reconstructions, resulting in considerably lower maximum elevations for the Laurentide and European ice sheets. The Laurentide has greater volume in ICE-5G than ICE-4G, and the Keewatin Dome is 2–3 km higher over much of central Canada, but the European ice~~Ice~~ sheet is less extensive in ICE-5G than ICE-4G.

The lowering of CO_2 makes a large contribution to the cooling at the LGM (Broccoli and Manabe, 1987; Hewitt and Mitchell, 1997; Broccoli, 2000; Kim, 2004; Otto-Bliesner et al., 2006; Brady et al., 2013), but the ice sheets (and the changes in albedo caused by the change in land-sea geography associated with the growth of these ice sheets and lowering of sea level) also have an important impact on both regional and global climates, particularly in the NH. Furthermore, the change in ice sheets~~land-sea geography has impacts on sea level and ocean circulation which directly~~ affects the carbon cycle and~~carbon cycle,~~ atmospheric CO_2 concentrations in~~and the~~ glacial cycles (Brovkin et al., 2012; Ganopolski and Calov, 2011; Abe-Ouchi et al., 2013). Ice-sheet height has major impacts on surface temperature via lapse rate, planetary-scale atmospheric circulation and the location of storm tracks, and hence precipitation patterns, and even on ocean circulation. ~~The magnitude of impacts on both the radiation balance (via albedo and lapse rate effect) and atmospheric circulation (planetary stationary wave, location of storm tracks), and the impact on the ocean, are all particularly sensitive to differences in the specification of ice-sheet height, and indeed~~Simulations~~simulations~~ using different ice sheet configurations have demonstrated these large differences both in global mean temperature and in NH circulation patterns and regional temperatures (Justino et al., 2005; Otto-Bliesner et al., 2006; Abe-Ouchi et al., 2007; Clark et al., 2009; Pausata et al., 2011; Vettoretti and Peltier, 2013; Ullman et al., 2014; Zhang et al., 2014).

At the time of the definition of the PMIP3 boundary conditions, there were several candidate ice-sheet reconstructions that could have been used as a boundary condition for the CMIP5/PMIP3 LGM simulations (ICE-6G v2.0: Argus and Peltier, 2010; GLAC-1a: Tarasov et al., 2012; ANU: Lambeck et al., 2010), which differ in the assumptions used in the modelling and in the type of data used as constraints on these models. The purpose of this paper is to explain the ice-sheet configuration that was used in the CMIP5/PMIP3 simulations, which was created by blending the three individual realisations, and to explore the consequences of this choice. This paper provides the information on the difference between the individual ice sheets and the blended ice sheet as well as ice sheet configuration of previous phases of PMIP. The individual ice sheet reconstructions are described in Sect. 2, and the procedure for creating the blended ice sheet is described in Sect. 3. The differences between this blended ice sheet, the individual ice sheet reconstructions, and previous ice sheet configurations used by PMIP, and their impact on forcing and climate, are discussed in Sect. 4. The final section of the paper highlights the uncertainties associated with the specification of the CMIP5/PMIP3 ice sheet. It ~~and~~ makes recommendations for further work to investigate the impact of ice sheet configuration on climate change as well as to minimise these uncertainties.

2 Documentation of the original ice-sheet reconstructions

2.1 ICE-6G v2.0 ice reconstruction

ICE-6G is the latest of a series of inversions of a glacial isostatic adjustment (GIA) model based on the solution for the impulse response of a viscoelastic Earth to surface loading described by Peltier (1974), in which global ice history and radial Earth viscosity profiles are repeatedly tuned to improve model predictions of relative sea-level (RSL) histories and present-day deformation rates compared to observations (Peltier and Andrews, 1976; Peltier, 1976; Tushingham and Peltier, 1991; Peltier, 1994, 2002, 2004; Argus and Peltier, 2010; Engelhart et al., 2011). The model is based upon detailed and continuously updated analyses of data of each of the previously glaciated regions (North America: Peltier, 2004; Argus and Peltier, 2010; Fennoscandia: Peltier, 2004; Argus and Peltier, 2010; Greenland: Tarasov and Peltier, 2002, 2004; the British Isles: Peltier, 2002; Shennan et al., 2002; Patagonia: Peltier, 2004; and Antarctica: Peltier, 2004), where each regional analysis is performed in a global context to yield a globally consistent response. In the most recent versions of the model, including the one used as an input to the CMIP5/PMIP3 composite ice sheet, satellite geodetic data (e.g. GPS, GRACE) is used to provide additional constraints (Peltier and Drummond, 2008; Argus and Peltier, 2010). ICE-4G (Peltier, 1994) was used to define the land-sea mask, the ice sheet extent and elevation, and land-surface topography and palaeo-ocean bathymetry in the first phase of PMIP (PMIP1) and ICE-5G (Peltier, 2004) in the second phase of PMIP (PMIP2). ICE-5G was improved relative to ICE-4G largely through the incorporation of revised information about the extent of the Eurasian ice sheets at the LGM from the QUEEN project (Svendsen et al., 1999; Mangerud et al., 2001, 2002; Svendsen et al., 2004) and the use of gravity changes across North America from the GRACE satellite as an additional constraint.

ICE-6G (or more precisely ICE-6G version 2.0 VM5a T60 Rot) differs from previous inversions through more extensive use of geodetic data as a constraint, including e.g. the global positioning satellite (GPS), satellite laser ranging (SLR), Very Long Baseline Interferometry (VLBI), and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS). The model uses the VM5a mantle viscosity profile with an elastic lithosphere thickness of 60 km (T60). VM5a is a three-layer approximation of the VM2 T90 profile described by Peltier and Drummond (2008), in which the lithosphere consists of a 60 km thick elastic layer above a 40 km thick layer that is higher viscous. This modification was made to improve the fit of the model to observations of horizontal displacement rates in North America. ICE-6G also takes account of the Earth's rotational effect (Rot) on the geoid. The sea-level predictions from ICE-6G have been shown to provide a good fit to several hundred Holocene RSL curves (Argus and Peltier, 2010), including Holocene RSL observations for the Caribbean Sea and the Atlantic coast of North America (Engelhart et al., 2011; Toscano et al., 2011). Engelhart et al. (2011) showed that a further improvement to the match between observations and predictions for the southern part of the Atlantic coast could be obtained by reducing the viscosity on the upper mantle (above $660\,\mathrm{km}$) from $0.5 \times 10^{21}\,\mathrm{Pa\,s}$ (VM5a) to $0.25 \times 10^{21}\,\mathrm{Pa\,s}$ (VM5b). However, subsequent work (Roy and Peltier, 2015). has shown that an even better match is obtained by reducing the viscosity of the upper part of the lower mantle.

2.2 GLAC-1a ice reconstruction

The GLAC-1a reconstruction is based on a set of glaciological models that are derived from a plausible climate forcing based on PMIP1 and PMIP2 results for LGM and that fit independently derived ice margin chronologies, within explicit uncertainties. The climate forcing involves an interpolation between present day observed climatologies and the set of highest resolution LGM fields from PMIP1 and PMIP2 data sets. The interpolation is weighted according to a glaciological inversion of the GRIP record (Tarasov and Peltier, 2003) for regional temperatures over the last glacial cycle.

The North American and Eurasian reconstructions are derived from separate Bayesian calibrations of the Glacial Systems Model (GSM). The GSM incorporates a 3-D thermo-mechanically coupled ~~shallow~~ ice-sheet model based on the shallow ice approximation, a permafrost resolving bed thermal model, an asynchronously coupled down-slope surface drainage/lake depth solver, and also includes thermodynamic lake ice, sub-glacial till-deformation, buoyancy and temperature dependent ice calving, and an ice-shelf representation (Tarasov and Peltier, 2004, 2005, 2007; Tarasov et al., 2012). The visco-elastic bedrock response uses either the VM2 (as used in ICE-5G) or VM5a (used in ICE-6G) earth rheologies. RSL is computed using a gravitationally self-consistent formalism similar to that of Peltier (2009), except that it includes an eustatic approximation for dealing with changing ocean masks and does not take account of Earth rotational effects (Tarasov et al., 2012).

Separate calibrations are made for North America and Eurasia. The calibration involves 36 ensemble parameters for North America and 29 ensemble parameters for Eurasia, to capture uncertainties in deglacial climate and ice dynamics. The majority of these parameters are used for the climate forcing, including weighting the Empirical Orthogonal Functions (EOFs)~~the EOFS~~ between PMIP models for LGM monthly precipitation and temperature, regional desert elevation effects, and LGM atmospheric lapse rate. Other ensemble parameters adjust the calving response, the effective viscosity of subglacial till, the strength of the ice-marginal constraint, and flow parameters for ice-shelves. Model runs are forced to stay within uncertainties of independently derived ice margin chronologies for North America (Dyke, 2004) and Eurasia (Hughes et al., 2014). Calibration targets include RSL observations from 512 sites (Tarasov and Peltier, 2002), geologically-inferred deglacial ice-margin chronologies, and geodetic constraints from Argus and Peltier (2010). In the case of North America, the calibrated ensemble is further scored with respect to strand-lines (paleo lake-level indicators) and observations of the maximum level of marine inundation. Model runs are penalised in proportion to the amount of margin correction (or "margin forcing", see section 2.4 of Tarasov and Peltier, 2004)~~forcing~~ required, so the calibration is directed towards a climate forcing that is consistent with the margin chronology.

The model was originally calibrated using the ICE-4G ice load reconstruction for Antarctica and the VM2 Earth rheology. However, the subsequent use of an expanded geodetic data-set for North America coupled with the significant reduction in LGM Antarctic ice volume in ICE-6G v.2 compared to ICE-4G led to a significant misfit with the far-field Barbados RSL record. A random 2000 member ensemble was generated along with a rerun of the best 300 previously calibrated parameter sets and some 200 attempts at hand-tuning. There is a significant tradeoff between fitting the Barbados constraint and fitting the constraints from other locations. In order to satisfy the Barbados constraint, the 1.5 sigma upper limit of the previously calibrated ensemble for North America (which almost reaches the inferred Barbados record for 26 to 21 ka) was used. A weighted ensemble mean of the model runs that passed hard threshold constraints in the previous calibration was used for North America. The Eurasian calibration converged and was successful, except for minor issues with the Norwegian fjords. A single run with the largest 26 ka RSL contribution to the Barbados record was therefore used. A single run was chosen to ensure consistency between drainage fields and the surface topography. The Greenland model is from Tarasov and Peltier (2002, 2003), a glaciological model with hand-tuned climate adjustments to enforce fit to RSL records and the GRIP borehole temperature record.

2.3 ANU ice reconstruction

The ANU reconstruction has also evolved over a period of years in an iterative fashion (Lambeck and Johnston, 1998; Lambeck and Chappell, 2001; Lambeck et al., 2014). The first iterations were based on the analysis of far-field sea-level data, where the sea-level signal is predominantly a measure of the changes in total ice volume (the ice-volume equivalent sea level or ESL). The principle isostatic contribution to these sea levels is from the change in water load, a function of the rate at which water is added into or removed from the oceans and how it is distributed within ocean basins. Simple models were initially used for the ice sheets. The separation of mantle rheology from the ESL function was achieved by using the spatial variability of the far-field sea-level signals (Nakada and Lambeck, 1989). The resulting ice volume was then redistributed between the ice sheets using scaling relations initially and iterating between far-field and near-field solutions to ensure convergence (Lambeck et al., 2002, 2014).

Inversions were also made for individual NH ice sheets using new compilations of field data from within and close to the ice margins, which are sensitive to the ice model and mantle rheology. Separate reconstructions have been made for Scandinavia (Lambeck et al., 1998, 2010), the Barents-Kara region (Lambeck, 1995a, 1996), Greenland (Fleming and Lambeck, 2004), the British Isles (Lambeck, 1993, 1995b), and North America (Lambeck, Purcell and Zhao, unpublished). These separate solutions allow lateral variability in mantle viscosity beneath the individual ice sheets to be detected, as well as differences between oceanic and continental mantle (Lambeck and Chappell, 2001). Some interactions occur between the separate ice sheet solutions requiring further iterations as each ice-sheet model is modified.

The field data from Antarctica is insufficient to use a similar approach to reconstruct ice-volume changes. Volume changes for the Antarctic ESL were obtained as the difference between the global ESL (Lambeck et al., 2014) and the NH ESL, the latter being the sum of the individual ice sheet contributions, and including mountain deglaciation in both hemispheres (Lambeck and Purcell, 2005). The ice in Antarctica was then distributed using the LGM ice margins proposed by Anderson et al. (2002), and assuming the ice profiles followed the quasi-parabolic function proposed by Paterson (1994). The retreat history is determined by the difference between the global ESL function and the combined northern-hemisphere mountain-glacier contributions. This reconstruction is not meant to be an accurate reflection of Antarctic ice history. Rather it is a convenient way of disposing of ice volume that cannot be attributed to the NH ice sheets in a way that does not impact in a major way on the far-field and NH analyses.

Several iterations have been performed to combine the far-field and individual ice-sheet reconstructions. The results used to create the CMIP5/PMIP3 composite are based on solutions current in 2009. The inversions yield changes in ice thickness compared to the present-day volume of each ice sheet. Thus, the LGM ice thickness is obtained by adding the present-day ice thickness. The LGM ice elevation, with respect to sea level at the LGM is obtained by subtracting the sea-level change (geoid change beneath the ice sheet) from the LGM ice thickness. The ESL function used in these solutions is defined as all land ice and grounded ice on the shelves. The LGM ocean margin is defined by the ice-grounding line (Lambeck et al., 2003).

3 Construction of the composite CMIP5/PMIP3 ice sheets

3.1 Terminology

We use the term topography to refer to the elevation~~altitude~~ of the upper ice surface if the land is covered by ice, including floating ice, or the elevation~~altitude~~ of the land surface or ocean floor in areas not covered by ice or floating ice. Topography can be expressed either relative to modern sea level or relative to the sea level at a specific time t. We use $\mathrm{Topo}(t)$ for topography relative to the sea level at time t, and $\mathrm{topo}(t)$ for topography expressed relative to modern sea level (i.e. when t is 0).

Surface elevation~~altitude~~ (Surf) is the elevation~~altitude~~ of the bottom of the atmosphere. $\mathrm{Surf}(t)$ is defined as:

$$\mathrm{Surf}(t) = \max\left[0, \mathrm{Topo}(t)\right], \tag{1}$$

which is 0 for ocean grid points and topography otherwise. Bathymetry (Bath) is the elevation~~altitude~~ of the ocean-floor under ice-shelves or topography otherwise.

There are four components that need to be provided to define ice-sheet related boundary conditions at the LGM: the difference in surface elevation~~altitude~~ (ΔSurf), an ice mask ($\mathrm{Mask}_\mathbf{1}$), an ice/shelf mask ($\mathrm{Mask}_\mathbf{2}$) and a land/sea mask ($\mathrm{Mask}_\mathbf{3}$). The first term (ΔSurf) is the difference in the surface elevation~~altitude~~ between LGM and the present-day. The three masks define the conditions at individual grid points~~, and~~. In the ice mask ($\mathrm{Mask}_\mathbf{1}$), 0 indicates ice-free and 1 indicates ice-covered grid points, including floating ice points. In the ice/shelf mask ($\mathrm{Mask}_\mathbf{2}$), 0 indicates ice-free points, 1 indicates grounded ice, and 2 indicates floating ice grid points. In the land/sea mask ($\mathrm{Mask}_\mathbf{3}$), 0 indicates land and 1 indicates ocean grid points. This information is provided for the domain from -180 to $179°$ in longitude and -89.5 to $89.5°$ in latitude, at a spatial resolution of $1° \times 1°$.

3.2 Conversion to common grid

The difference in the surface elevation~~altitude~~ at the LGM can be computed as:

$$\Delta\mathrm{Surf}(21\,\mathrm{ka}) = \mathrm{Surf}(21\,\mathrm{ka}) - \mathrm{Surf}(0\,\mathrm{ka}). \tag{2}$$

However, each of the individual ice-sheet reconstructions provides different outputs corresponding to the terms on the right hand side of this equation (Table 1). ANU provides estimates of the change in thickness between LGM and present day (ΔThick) and relative sea level (RSL), GLAC-1a provides Thick and $\mathrm{topo}(21\,\mathrm{ka})$, while ICE-6G provides $\mathrm{Topo}(21\,\mathrm{ka})$ and bathymetry $\mathrm{Bath}(21\,\mathrm{ka})$ as well as providing explicit masks for 21 and 0 ka. In order to produce the composite CMIP5/PMIP3 data set, it was therefore necessary to transform the original outputs before interpolating these data onto a common grid.

The domain of ICE-6G v2.0 is the same as that used in the composite CMIP5/PMIP3 reconstructions, so no spatial transformation was needed. The difference in the surface elevation at the LGM compared to the present day was computed from the original variables as:

$$\Delta\mathrm{Surf}(21\,\mathrm{ka}) = \max\left[0, \mathrm{Topo}(21\,\mathrm{ka})\right] - \max\left[0, \mathrm{Topo}(0\,\mathrm{ka})\right]. \tag{3}$$

The ice mask, $\mathrm{Mask}_\mathbf{1}(21\,\mathrm{ka})$, was extracted directly from the original reconstruction. The ice/shelf mask, $\mathrm{Mask}_\mathbf{2}(21\,\mathrm{ka})$, was computed from Topo and Bath as:

$$\mathrm{Mask}_\mathbf{2}(21\,\mathrm{ka}) = \begin{cases} 2 & \text{if Topo} \neq \text{Bath}, \\ \mathrm{Mask}_\mathbf{1} & \text{otherwise}. \end{cases} \tag{4}$$

The ANU reconstruction provides RSL and (ΔThick) for four separate regions (Table 1). RSL over the British Isles was computed under the assumption that the present-day is in equilibrium, with a mantle density of $4500\,\mathrm{kg\,m^{-3}}$. These terms were first interpolated to the PMIP3 spatial grid, but no attempt was made to attribute values to gridpoints beyond those covered by the original data set.

The LGM topography was computed as:

$$\text{Topo}(21\,\mathrm{ka}) = \text{Topo}(0\,\mathrm{ka}) + \Delta\text{Thick} - \text{RSL}\,, \tag{5}$$

where Topo$(0\,\mathrm{ka})$ was derived from the ETOPO1 data set (Amante and Eakins, 2009). Ice-covered grid points that were still under $0\,\mathrm{m}$ (i.e. sea level elevation) after this procedure were corrected using an ice-floating adjustment, using ice and water densities 910 ~~kg m−3~~ and $1028\,\mathrm{kg\,m^{-3}}$ respectively. Topography was then converted to ΔSurf using Eq. (3). There are several grid cells (e.g. near ice divides) where ice is present but $\Delta\text{Thick} = 0$. A modern reference ice mask is therefore required to compute the LGM ice mask for the ANU reconstruction. The LGM ice mask was therefore computed as:

$$\text{Mask}_{\mathbf{1}}(21\,\mathrm{ka}) = \begin{cases} 0 & \text{if Topo} \neq \text{Bath}, \\ 1 & \text{else if ICE-6G Mask}_{\mathbf{1}} = 1\,, \\ 1 & \text{else if } \Delta\text{Thick}(21\,\mathrm{ka}) > 0\,, \\ 0 & \text{otherwise}\,. \end{cases} \tag{6}$$

The ice/shelf mask was computed as:

$$\text{Mask}_{\mathbf{2}} = \begin{cases} 2 & \text{if Topo}(21\,\mathrm{ka}) < 0\,, \\ 1 & \text{if Mask}_{\mathbf{1}} = 1\,, \\ 0 & \text{otherwise}\,. \end{cases} \tag{7}$$

The GLAC-1a reconstruction provide Thick$(21\,\mathrm{ka})$ and topo$(21\,\mathrm{ka})$ for North America and Eurasia, and specifies the global sea level change of $116\,\mathrm{m}$. The topography relative to LGM sea level is computed as:

$$\text{Topo}(21\,\mathrm{ka}) = \text{topo}(21\,\mathrm{ka}) + 116\,\mathrm{m}\,. \tag{8}$$

The resulting values were then interpolated to the PMIP3 grid, although no attempt was made to attribute values to gridpoints beyond those covered by the original data set (i.e. Antarctica). Gridpoints that were ice-covered but below sea level were corrected using the same floating-ice adjustment as used for the ANU reconstruction. ΔSurf was then computed using Eq. (3). The ice mask was computed from Thick$(21\,\mathrm{ka})$ as:

$$\text{Mask}_{\mathbf{1}} = \begin{cases} 0 & \text{if Thick}(21\,\mathrm{ka}) = 0\,, \\ 1 & \text{otherwise}\,. \end{cases} \tag{9}$$

The ice/shelf mask was computed using Eq. (7).

3.3 Integration of the three reconstructions

The CMIP5/PMIP3 composite ice-sheet reconstruction was created from the three transformed individual reconstructions. The LGM ice mask was taken as the maximum possible coverage:

$$\text{Mask}_{\mathbf{1},\text{ave}} = \begin{cases} 1 & \text{if at least one of the three Mask}_{\mathbf{1}} \text{ is } 1\,, \\ 0 & \text{otherwise}\,. \end{cases} \tag{10}$$

The surface elevation~~altitude~~ for ice-free grid cells was taken from ICE-6G v.2, while the difference in the surface elevation~~altitude~~ for ice-covered grid cells was computed by averaging the three reconstructions:

$$\Delta\text{Surf} = \begin{cases} (\Delta\text{Surf}'(\text{ANU}) + \Delta\text{Surf}'(\text{ICE-6G}) + \\ \Delta\text{Surf}'(\text{GLAC-1}))/N_\text{d} & \text{where Mask}_{\mathbf{1},\text{ave}} = 1\,, \\ \\ \Delta\text{Surf(ICE-6G)} \qquad \text{otherwise}\,, \end{cases} \tag{11}$$

where N_d is the number of individual datasets (i.e. between 1 and 3) which provide a value for ΔSurf for a given grid-point, and $\Delta\text{Surf}'$ is the surface elevation field extended over undefined gridpoints such that~~the masked surface altitude such as~~:

$$\Delta\text{Surf}' = \begin{cases} \Delta\text{Surf} & \text{if defined}\,, \\ 0 & \text{if undefined (no quantity)}\,. \end{cases} \tag{12}$$

The ice/shelf mask is computed as minimum possible shelf coverage.

$$\text{Mask}_{\mathbf{2},\text{ave}} = \begin{cases} 1 & \text{if at least one of the three Mask}_{\mathbf{2}} \text{ is } 1\,, \\ 0 & \text{if all of the three Mask}_{\mathbf{2}} \text{ are } 0\,, \\ 2 & \text{otherwise}\,. \end{cases} \tag{13}$$

The resulting mask had five glaciated grid points where ΔSurf was anomalously much lower than the surrounding points. We took the average value of the surrounding grid points, in order to avoid unrealistic spatial variability in ice-sheet topography. The present-day area of the Caspian Sea was included in the LGM land/sea mask, and a small number of land gridcells spuriously assigned to ocean were also corrected.

4 Comparison of the ice-sheet reconstructions

4.1 Comparison of the individual ice sheet reconstructions

The ANU reconstruction shows larger changes in all of the individual ice sheets than shown by either the GLAC-1a or the ICE-6G v.2 reconstruction, while the GLAC-1a reconstruction shows smaller changes in NH ice sheet volume than the other two reconstructions~~The ANU reconstruction~~

~~consistently shows the largest changes and GLAC-1a reconstruction the smallest changes in NH ice sheet volume~~ (Table 2). The estimates for the Laurentide Ice Sheet, when expressed in terms of eustatic sea level, vary from 83 to 77 m, and the estimates for the Eurasian ice sheet~~Ice Sheet~~ from 18 to 14 m. The GLAC-1a reconstruction shows the Laurentide Ice Sheet as a single broad dome, with maximum elevations ($< 3000\,\mathrm{m}$) in the west (Fig. 1). ICE-6G v.2 also shows maximum elevations in the western part of the ice sheet, but has a smaller secondary maximum over the James Bay area (Fig. 1). A larger part of the Laurentide Ice Sheet has elevations $> 3000\,\mathrm{m}$ in the ANU reconstruction (Fig. 1). The GLAC-1a and ICE-6G v.2 reconstructions for Greenland are similar (because they are essentially derived from the same model: see Tarasov and Peltier, 2002, 2004) and show a flatter ice sheet with increased elevations around the margin and somewhat lower elevations than today in the centre (Fig. 2). The ANU reconstruction does not show lower central elevations, but does have an increase in marginal elevations. All three reconstructions show the Eurasian ice sheet~~Ice Sheet~~ with two major domes, one centred upon the Gulf of Bothnia and the other over the Barents Sea. The ANU reconstruction has elevations $> 3000\,\mathrm{m}$ for the western dome, whereas both domes are of similar and lower (2000–3000 m) elevations in the ICE-6G v.2 and GLAC-1a reconstructions (Figures 1, 2).~~The ANU reconstruction has elevations $> 3000\,\mathrm{m}$ for the western dome, but both ICE-6G v.2 and GLAC-1a show similar and lower (2000–3000 m) elevations for both parts of the Eurasian Ice Sheet (Figs. 1, 2).~~

Only ICE-6G v.2 and ANU provide independent reconstructions of Antarctica. The volumetric change, when expressed in terms of eustatic sea level, is nearly twice as large in the ANU reconstruction (29 m) than in the ICE-6G v.2 reconstruction (15.6 m) (Table 2). More of the eastern part of the ice sheet lies at elevations $> 3000\,\mathrm{m}$ in the ANU reconstruction (Fig. 3), whereas the ICE-6G v.2 reconstruction has a secondary dome at elevations $> 3000\,\mathrm{m}$ over the Marie Byrd region which is not present in the ANU reconstructions. In both reconstructions, the major differences in elevation between the LGM and present are in western Antarctica, where elevation is higher by ca 900 m at the LGM than today (Fig. 4). The area of increased elevation is larger in the ANU reconstruction than in the ICE-6G v.2 reconstruction.

Although all of the individual reconstructions are constructed using information on the location of the margins of each ice sheet, nevertheless the final reconstructed extent of the ice sheets is derived from the inverse model. Thus, there may be discrepancies between the reconstructions and the actual, observed location of the LGM margins of each ice sheet. There are indeed differences between the ice and ice/shelf and land/sea masks obtained from each of the individual reconstructions. The implied change in eustatic sea level (Table 2) is larger in the ANU reconstruction than in the ICE-6G v.2 reconstruction. Similarly, the extent of ice shelves is consistently smaller in the ICE-6G v.2 reconstruction than in the ANU reconstruction, both for the NH and around Antarctica (Fig. 5).

4.2 Comparison of the CMIP5/PMIP3 composite reconstruction with earlier PMIP ice sheets

Ice sheet reconstructions used in the first two phases of PMIP were based on earlier versions of the ICE-6G inversion approach: ICE-4G (Peltier, 1994) for the first phase of PMIP (PMIP1) and ICE-5G (Peltier, 2004) for the second phase of PMIP (PMIP2). ICE-5G was improved relative to ICE-4G through the incorporation of revised information about the extent of the Eurasian ice sheets at the LGM from the QUEEN project (Svendsen et al., 1999; Mangerud et al., 2001, 2002; Svendsen et al., 2004). ICE-6G differs from ICE-5G because of the inclusion of constraints based on satellite geodetic data as well as a more extensive data set of relative sea level changes. The differences between the three reconstructions are substantial. The PMIP2 NH ice sheets are considerably higher than the CMIP5/PMIP3 composite ice sheet while the PMIP1 NH ice sheets are lower than the CMIP5/PMIP3 composite and do not show the pronounced dome in the western part of the Laurentide (Figs. 1, 2). The Eurasian ice sheet is less extensive in the CMIP5/PMIP3 composite reconstruction than in the earlier reconstructions and~~but~~ maximum elevations are lower than in the earlier PMIP reconstructions. In contrast, the region of western Antarctica characterised by large changes ($< 900\,\mathrm{m}$) is more extensive in the CMIP5/PMIP3 composite reconstruction than in the earlier reconstructions, though this is partly due to the higher spatial resolution of the composite ice sheet compared to the earlier reconstructions.

4.3 Magnitude of CMIP5/PMIP3 composite ice-sheet forcing

The implied forcing resulting from the change in ice sheets and land-sea geography given by the CMIP5/PMIP3 composite is estimated using the Taylor et al. (2007) approximate partial-radiative perturbation method. The method is based on a simplified shortwave radiative model of the atmosphere. Surface absorption, atmospheric scattering and absorption are represented by means of three parameters that are diagnosed at each grid cell from surface and top-of-the-atmosphere fluxes and albedo. These parameters are different in each model and simulation, and reflect the properties of the radiative code in the individual models, and the differences of these terms in the different time periods. To quantify the effect of the change of each of these parameters, the parameters in the simple model are perturbed individually by the amount that they change in the climate response in order to compute the corresponding radiative change. We adopted a two-sided approach, in which two estimates of the radiative change are made considering the control simulation and the palaeo-simulation in turn as a reference. According to these calculations, the forcing resulting from the change in the ice-sheet alone~~the ice-sheet change~~ is between -1.85 and $-3.49\,\mathrm{W\,m^{-2}}$ depending on the climate model (Table 3), while the total~~overall~~ change in forcing resulting from the imposition of LGM boundary conditions varies between -3.62 and $-5.20\,\mathrm{W\,m^{-2}}$. The difference in forcing in simulations using the CMIP/PMIP composite (Fig. 6) and the PMIP2 ice sheet is ca $1.0\,\mathrm{W\,m^{-2}}$. Technically, the estimated difference in forcing between the PMIP2 and CMIP5/PMIP3 simulations obtained through these analyses reflects both differences in the ice sheet reconstruction (other boundary conditions are the same in the two sets of experiments) and differences in the version of the model used for the PMIP2 and CMIP5/PMIP3 experiments. Only three modeling groups (CCSM, IPSL, MIROC) have made LGM simulations in using both the PMIP2 and CMIP5/PMIP3 ice sheets. They show an average change in total forcing of $1.34\,\mathrm{W\,m^{-2}}$ with the change in radiative forcing caused by the ice sheet is ca $1\,\mathrm{W\,m^{-2}}$, i.e. of comparable magnitude to the estimate obtained from the ensemble mean. The impact of changes in individual model configuration would be unlikely to yield the systematic increase in forcing between PMIP2 and CMIP5/PMIP3 shown by these three models. Thus, it seems plausible that the estimate of the effect of using the CMIP5/PMIP3 ice sheet obtained by comparing the PMIP2 and CMIP5/PMIP3 ensemble of simulations is realistic.

4.4 Impact of differences between the ice-sheet reconstructions on climate

To evaluate the impact of elevation differences between the individual ice sheets and the CMIP5/PMIP3 composite ice sheet on surface climate, we have run simulations with atmosphere-slab ocean version of the MIROC3 model assuming no change in ocean heat transport from the control run and no change in ocean mask. Using different ice sheet reconstructions has an impact on surface temperature over the ice sheets themselves, and in adjacent regions of the ocean (Arctic, North Atlantic and~~North Atlantic,~~ Southern Ocean), and a smaller impact over the Northern Hemisphere partly through the influence on atmospheric stationary wave (Fig. 7). The largest differences from the CMIP5/PMIP composite occur where the reconstructions differ in terms of the ice extent (e.g. between North America and Greenland) or elevation~~altitude~~ (e.g. western Antarctica, Scandinavian ice sheet). The ANU reconstruction produces slightly colder temperatures in the Arctic than either ICE-6G v.2 or GLAC-1a. The largest discrepancy occurs over Antarctica, where regional differences in temperature can be $> 6\,^{\circ}\mathrm{C}$ between the simulations using the ICE-6G v.2 and ANU reconstructions (Fig. 7).

According to the MIROC simulations (Fig. 7), the overall impact of using the CMIP5/PMIP3 composite ice sheet in preference to any individual reconstruction is smaller than the difference between the CMIP5/PMIP3 composite and the ICE-5G ice sheet used in the PMIP2 simulations. Comparison of the multi-model ensemble from PMIP2 and CMIP5/PMIP3 (Fig. 8) shows that the decision to move to a new generation of ice sheet reconstructions has a large impact on simulated LGM climate, not only in regions adjacent to the ice sheets but also over the ocean and in the tropics. Based on these ensemble results, the use of the CMIP5/PMIP3 composite ice sheet together with the development of climate models produces additional reduction of ca $0.5\,^{\circ}\mathrm{C}$ in global~~an increase in global~~ mean annual temperature ~~of ca 0.5 °C~~ compared to the PMIP2 experiments.

5 Discussion and conclusions

There is currently no consensus about the form of the LGM ice sheets. Differences between existing reconstructions reflect the fact that new information is still emerging about the details of ice-sheet margins at the LGM and their retreat history, and the lithologic and geomorphic parameters that are used as constraints for ice-sheet modelling. While it is useful to explore the consequences of differences between reconstructions through sensitivity experiments, the use of a unified data set facilitates model-model intercomparison focusing on the role of structural differences between models. This was the motivation for the construction of a composite set of ice-sheet related boundary conditions for the CMIP5/PMIP3 LGM experiment. It is heartening that the differences between the individual reconstructions contributing to the composite are relatively small and have only a minor impact on simulated NH radiative forcing and temperature.~~In an ideal world, there would be a consensus about the form of the LGM ice sheets and thus no need to reconstruct a composite set of ice-sheet related boundary conditions. In reality, information is still emerging about the details of ice-sheet margins at the LGM, retreat history lithologic constraints and so on, and thus existing reconstructions differ. It is useful to explore the consequences of differences between reconstructions through sensitivity experiments, but model-model intercomparison is facilitated by the use of a single set of boundary conditions, which then allows a focus on the role of structural differences between models. It is heartening that the differences between the individual reconstructions contributing to the composite are relatively small and have only a minor impact on simulated NH radiative forcing and temperatures.~~

The differences between the CMIP5/PMIP3 composite ice sheet and the ice sheets used in LGM simulations made during earlier phases of PMIP are not negligible. Braconnot et al. (2012) estimated that the difference between the prescribed~~implied~~ land-sea mask from the PMIP2 and CMIP5/PMIP3 ice sheet would result in an additional $0.6\,\mathrm{W\,m^{-2}}$ forcing in the CMIP5/PMIP3 simulations, while the difference in ice-sheet height would result in temperatures ca $0.6\,^{\circ}\mathrm{C}$ warmer than in the PMIP2 experiments. We estimate that, in fact, the difference in forcing in simulations using the CMIP/PMIP composite and the PMIP2 ice sheet is ca $1.0\,\mathrm{W\,m^{-2}}$ and the average (ensemble) difference in the global mean annual temperature anomaly is ca $0.5\,^{\circ}\mathrm{C}$. These estimates are derived from the ensemble of simulations made for each set of experiments, and thus we cannot exclude a contribution from changes in model configuration to the apparent difference in forcing and temperature response between the PMIP2 and CMIP5/PMIP3 results. However, the three models from the ensemble which performed both sets of experiments all show an estimate of a difference in forcing due to ice sheet configuration of ca $1.0\,\mathrm{W\,m^{-2}}$, which suggests that this is a result of a systematic difference in the simulation protocol rather than the non-systematic changes that might be expected to result from changes in model configuration. While it would clearly be useful for a larger number of modeling groups to test the impact of ice sheet configuration, it seems plausible that the use of the CMIP5/PMIP3 ice sheet results in an increase of radiative forcing of ca $1.0\,\mathrm{W\,m^{-2}}$ compared to the previous generation of PMIP simulations. The climate difference is non-negligible over the

North Atlantic and over the continents of Northern Hemisphere both due to radiative forcing and the atmospheric circulation change in multi models as well as the MIROC model sensitivity test.

Sensitivity experiments using the MIROC model show that the decision to use a composite ice sheet, rather than any of the existing ice-sheet realisations, does have an impact on simulated climate. The differences, however, are largely confined to the ice sheets themselves and adjacent oceans and basically reflect disagreements between the independent reconstructions about ice extent and/or elevation~~altitude~~. The choice makes little difference to simulated temperatures beyond the ice-sheet margins. Nevertheless, over the ice sheets the differences in surface temperature can be large ($> 5\,^{\circ}\mathrm{C}$) and this could have a non-negligible impact on other aspects of the surface climate (see e.g. Chavaillaz et al., 2013) and ocean circulation. Testing the response of a fully coupled atmosphere-ocean model to these three reconstructions is beyond the scope of the present paper, but we would anticipate larger changes than in the atmosphere-slab ocean experiments, notably through the impact of the different reconstructions on westerly winds over the North Atlantic which can, in turn, have an impact on the Atlantic Meridional Overturning Circulation (Ullman et al., 2014; Zhang et al., 2014). Thus, it is important that the differences between the reconstructions are examined carefully so that better-constrained reconstructions are available for future PMIP analyses. However, simulations made with the composite CMIP5/PMIP3 ice sheet have more realistic temperatures over Antarctica, falling within or very close to the uncertainty range of estimates of the LGM cooling derived from ice core data, than the majority of PMIP2 simulations (Masson-Delmotte et al., 2013). While this may reflect model improvements to some extent, it would be unlikely to occur if the ice-sheet configuration of~~configuration in the~~ CMIP5/PMIP3 was~~simulations were~~ substantially wrong.

There are differences~~discrepancies~~ between the actual, observed~~observation~~ margin of each ice sheet at the LGM and the margins reconstructed by inverse modelling. Furthermore, the way in which ice-sheet topography and extent are implemented varies between different climate models. Thus, there may be differences between the CMIP5/PMIP3 ice sheet mask and the mask used by an individual model (see e.g. Chavaillaz et al., 2013; Fig. 9). Both of these issues could be important in the processing of model outputs for model-model or data-model comparison. This is clearly an issue that needs to be addressed more fully in the design of palaeo-simulations for the next phase of CMIP (CMIP6). Changes in palaeo-bathymetry, which is one output that can be obtained from the ice sheet models (e.g. ICE-6G v.2) have rarely been implemented in a coupled ocean-atmosphere model context. The implications of palaeo-bathymetry changes for ocean circulation could be important, and again this is an issue that could be addressed in the future design of palaeo-experiments.

Our knowledge of the LGM ice-sheet/ice-shelf reconstruction~~margins~~ is continually improving, as are the models that are used to reconstruct the most likely distribution of ice mass (Whitehouse et al., 2012; Anderson et al., 2014; Bentley et al., 2014; Mackintosh et al., 2014; Briggs et al., 2014; Lambeck et al., 2014; Peltier et al., 2015; Hall et al., 2015). Indeed~~, and indeed~~ there have been updated reconstructions of LGM ice sheet configuration since the CMIP5/PMIP3 ice sheet was constructed. For example, the ICE-6G_C (VM5a) reconstruction is an updated version of the ICE-6G(VM5a) v2.0 model discussed here, and informed by a much richer data base of space geodetic information (Argus et al., 2014; Peltier et al., 2015). It is inevitable that there will be further changes in the future, although less clear when there will be a consensus about their form. It is imperative, then, that a wider range of models conduct sensitivity tests to the impact of ice sheet configuration, focusing on both near-field and remote impacts on climate.~~What is imperative, then, is that a wider range of models conduct sensitivity tests to the impact of ice sheet configuration.~~ This would make it possible to draw on the wealth of palaeoclimate data from beyond the ice sheets to evaluate, and perhaps even constrain, ice-sheet reconstructions.

The Supplement related to this article is available online at doi:10.5194/gmd-0-1-2015-supplement.

Acknowledgements. ~~This paper is a contribution to the ongoing work on the Palaeoclimate Modelling Intercomparison Project.~~ We thank Rosemarie Drummond ~~,Jun'ici Okuno~~ and Rumi Ohgaito for technical assistance. We thank to Catherine Ritz, Peter Clark, Anders Carlson, Jun'ichi Okuno, Heinz Blatter, all of those who contributed to the PMIP Wiki and the participants in the PMIP and PALSEA workshops for scientific discussion. We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modeling groups (listed in Table 3 of this paper) for producing and making available their model output. For CMIP the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals. The numerical experiments by the MIROC model were carried out on the JAMSTEC Earth Simulator. The research was supported by JSPS KAKENHI grant 25241005. This paper is a contribution to the ongoing work on the Palaeoclimate Modelling Intercomparison Project.

References

Abe-Ouchi, A., Segawa, T., and Saito, F.: Climatic Conditions for modelling the Northern Hemisphere ice sheets throughout the ice age cycle, Clim. Past, 3, 423–438, doi:10.5194/cp-3-423-2007, http://www.clim-past.net/3/423/2007/, 2007.

Abe-Ouchi, A., Saito, F., Kawamura, K., Raymo, M. E., Okuno, J., Takahashi, K., and Blatter, H.: Insolation-driven 100,000-year glacial cycles and hysteresis of ice-sheet volume, Nature, 500, 190–193, doi:10.1038/nature12374, http://dx.doi.org/10.1038/nature12374, 2013.

Alyea, F.: Numerical simulation of an ice age paleoclimate, Atmospheric Science Paper No. 193, Colorado State University, Fort Collins, Colorado, USA, 1972.

Amante, C. and Eakins, B.: ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis, NOAA Technical Memorandum NESDIS NGDC-24. National Geophysical Data Center, NOAA, Boulder, Colorado, USA, doi:10.7289/V5C8276M, 2009.

Anderson, J. B., Shipp, S. S., Lowe, A. L., Wellner, J. S., and Mosola, A. B.: The Antarctic Ice Sheet during the Last Glacial Maximum and its subsequent retreat history: a review, Quat. Sci. Rev., 21, 49–70, 2002.

Anderson, J. B., Conway, H., Bart, P. J., Witus, A. E., Greenwood, S. L., McKay, R. M., Hall, B. L., Ackert, R. P., Licht, K., Jakobsson, M., and Stone, J. O.: Ross Sea paleo-ice sheet drainage and deglacial history during and since the {LGM}, Quat. Sci. Rev., 100, 31–54, doi:http://dx.doi.org/10.1016/j.quascirev.2013.08.020, http://www.sciencedirect.com/science/article/pii/S0277379113003338, reconstruction of Antarctic Ice Sheet Deglaciation (RAISED), 2014.

Argus, D. F. and Peltier, W. R.: Constraining models of postglacial rebound using space geodesy: a detailed assessment of model ICE-5G (VM2) and its relatives, Geophys. J. Int., 181, 697–723, doi:10.1111/j.1365-246X.2010.04562.x, http://dx.doi.org/10.1111/j.1365-246X.2010.04562.x, 2010.

Argus, D. F., Peltier, W. R., Drummond, R., and Moore, A. W.: The Antarctica component of postglacial rebound model ICE-6G_C (VM5a) based on GPS positioning, exposure age dating of ice thicknesses, and relative sea level histories, Geophys. J. Int., 198, 537–563, doi:10.1093/gji/ggu140, http://gji.oxfordjournals.org/content/198/1/537.abstract, 2014.

Bartlein, P. J., Harrison, S. P., Brewer, S., Connor, S., Davis, B. A. S., Gajewski, K., Guiot, J., Harrison-Prentice, T. I., Henderson, A., Peyron, O., Prentice, I. C., Scholze, M., Seppa, H., Shuman, B., Sugita, S., Thompson, R. S., Viau, A. E., Williams, J., and Wu, H.: Pollen-based continental climate reconstructions at 6 and 21 ka: a global synthesis, Clim. Dyn., 37, 775–802, doi:10.1007/s00382-010-0904-1, 2011.

Bentley, M. J., Cofaigh, C. Ó., Anderson, J. B., Conway, H., Davies, B., Graham, A. G., Hillenbrand, C.-D., Hodgson, D. A., Jamieson, S. S., Larter, R. D., Mackintosh, A., Smith, J. A., Verleyen, E., Ackert, R. P., Bart, P. J., Berg, S., Brunstein, D., Canals, M., Colhoun, E. A., Crosta, X., Dickens, W. A., Domack, E., Dowdeswell, J. A., Dunbar, R., Ehrmann, W., Evans, J., Favier, V., Fink, D., Fogwill, C. J., Glasser, N. F., Gohl, K., Golledge, N. R., Goodwin, I., Gore, D. B., Greenwood, S. L., Hall, B. L., Hall, K., Hedding, D. W., Hein, A. S., Hocking, E. P., Jakobsson, M., Johnson, J. S., Jomelli, V., Jones, R. S., Klages, J. P., Kristoffersen, Y., Kuhn, G., Leventer, A., Licht, K., Lilly, K., Lindow, J., Livingstone, S. J., Massé, G., McGlone, M. S., McKay, R. M., Melles, M., Miura, H., Mulvaney, R., Nel, W., Nitsche, F. O., O'Brien, P. E., Post, A. L., Roberts, S. J., Saunders, K. M., Selkirk, P. M., Simms, A. R., Spiegel, C., Stolldorf, T. D., Sugden, D. E., van der Putten, N., van Ommen, T., Verfaillie, D., Vyverman, W., Wagner, B., White, D. A., Witus, A. E., and Zwartz, D.: A community-based geological reconstruction of Antarctic Ice Sheet deglaciation since the Last Glacial Maximum, Quat. Sci. Rev., 100, 1–9, doi:http://dx.doi.org/10.1016/j.quascirev.2014.06.025, http://www.sciencedirect.com/science/article/pii/S0277379114002546, reconstruction of Antarctic Ice Sheet Deglaciation (RAISED), 2014.

Braconnot, P., Otto-Bliesner, B., Harrison, S., Joussaume, S., Peterschmitt, J.-Y., Abe-Ouchi, A., Crucifix, M., Driesschaert, E., Fichefet, T., Hewitt, C. D., Kageyama, M., Kitoh, A., Laîné, A., Loutre, M.-F., Marti, O., Merkel, U., Ramstein, G., Valdes, P., Weber, L., Yu, Y., and Zhao, Y.: Results of PMIP2 coupled simulations of the mid-Holocene and Last Glacial Maximum Part 1: experiments and large-scale features, Clim. Past, 3, 261–277, http://www.clim-past.net/3/261/2007/, 2007a.

Braconnot, P., Otto-Bliesner, B., Harrison, S., Joussaume, S., Peterschmitt, J.-Y., Abe-Ouchi, A., Crucifix, M., Driesschaert, E., Fichefet, T., Hewitt, C. D., Kageyama, M., Kitoh, A., Laîné, A., Loutre, M.-F., Marti, O., Merkel, U., Ramstein, G., Valdes, P., Weber, L., Yu, Y., and Zhao, Y.: Results of PMIP2 coupled simulations of the mid-Holocene and Last Glacial Maximum–Part 2: feedbacks with emphasis on the location of the ITCZ and mid- and high latitudes heat budget, Clim. Past, 3, 279–296, doi:10.5194/cp-3-279-2007, http://www.clim-past.net/3/261/2007/, 2007b.

Braconnot, P., Harrison, S. P., Kageyama, M., Bartlein, P. J., Masson-Delmotte, V., Abe-Ouchi, A., Otto-Bliesner, B., and Zhao, Y.: Evaluation of climate models using palaeoclimatic data, Nature Clim. Change, 2, 417–424, doi:10.1038/NCLIMATE1456, 2012.

Brady, E. C., Otto-Bliesner, B. L., Kay, J. E., and Rosenbloom, N.: Sensitivity to glacial forcing in the CCSM4, J. Climate, 26, 1901–1925, doi:10.1175/JCLI-D-11-00416.1, 2013.

Briggs, R. D., Pollard, D., and Tarasov, L.: A data-constrained large ensemble analysis of Antarctic evolution since the Eemian, Quat. Sci. Rev., 103, 91–115, doi:http://dx.doi.org/10.1016/j.quascirev.2014.09.003, http://www.sciencedirect.com/science/article/pii/S0277379114003448, 2014.

Broccoli, A. J.: Tropical Cooling at the Last Glacial Maximum: An Atmosphere-Mixed Layer Ocean Model Simulation, J. Climate, 13, 951–976, doi:10.1175/1520-0442(2000)013<0951:TCATLG>2.0.CO;2, http://dx.doi.org/10.1175/1520-0442(2000)013<0951:TCATLG>2.0.CO;2, 2000.

Broccoli, A. J. and Manabe, S.: The influence of continental ice, atmospheric CO_2, and land albedo on the climate of the last glacial maximum, Clim. Dyn., 1, 87–99, doi:10.1007/BF01054478, 1987.

Brovkin, V., Ganopolski, A., Archer, D., and Munhoven, G.: Glacial CO_2 cycle as a succession of key physical and biogeochemical processes, Clim. Past, 8, 251–264, doi:10.5194/cp-8-251-2012, http://www.clim-past.net/8/251/2012/, 2012.

Chavaillaz, Y., Codron, F., and Kageyama, M.: Southern westerlies in LGM and future (RCP4.5) climates, Clim. Past, 9, 517–524, doi:10.5194/cp-9-517-2013, http://www.clim-past.net/9/517/2013/, 2013.

Clark, P. U., Dyke, A. S., Shakun, J. D., Carlson, A. E., Clark, J., Wohlfarth, B., Mitrovica, J. X., Hostetler, S. W., and McCabe, A. M.: The Last Glacial Maximum, Science, 325, 710–714, doi:10.1126/science.1172873, 2009.

CLIMAP: Seasonal reconstructions of the Earth's surface at the last glacial maximum, no. MC-36 in Map Chart Series, Geological Society of America, Boulder, Colorado, 1981.

CLIMAP Project Members: The Surface of the Earth, Science, 191, 1131–1137, 1976.

Collins, M., Knutti, R., Arblaster, J., Dufresne, J.-L., Fichefet, T., Friedlingstein, P., Gao, X., Gutowski, W., Johns, T., Krinner, G., Shongwe, M., Tebaldi, C., Weaver, A., and Wehner, M.: Long-term climate change: projections, commitments and irreversibility, in: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by Stocker, T., Qin, D., Plattner, G.-K., Tignor, M., Allen, S., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013.

Dyke, A. S.: An outline of North American deglaciation with emphasis on central and northern Canada, in: Quaternary Glaciation — Extent and Chronology, Part II, edited by Ehlers, J. and Gibbard, P. L., vol. 26 of *Developments in Quaternary Science*, pp. 374–424, Elsevier, Amsterdam, the Netherlands, 2004.

Dyke, A. S. and Prest, V. K.: Late Wisconsinan and Holocene history of the Laurentide ice sheet, Géographie physique et Quaternaire, 41, 237–263, doi:10.7202/032681ar, https://www.erudit.org/revue/gpq/1987/v41/n2/032681ar.html?lang=en, 1987.

Ehlers, J., Gibbard, P. L., and Hughes, P. D.: Quaternary glaciations-extent and chronology: a closer look, vol. 15, Elsevier, Amsterdam, the Netherlands, 2011.

Engelhart, S. E., Peltier, W. R., and Horton, B. P.: Holocene relative sea-level changes and glacial isostatic adjustment of the U. S. Atlantic coast, Geology, 39, 751–754, 2011.

Fleming, K. and Lambeck, K.: Constraints on the Greenland Ice Sheet since the Last Glacial Maximum from sea-level observations and glacial-rebound models, Quat. Sci. Rev., 23, 1053–1077, doi:10.1016/j.quascirev.2003.11.001, http://www.sciencedirect.com/science/article/B6VBC-4BJ756Y-2/2/655967988f5822198a55a65af5345f88, 2004.

Ganopolski, A. and Calov, R.: The role of orbital forcing, carbon dioxide and regolith in 100 kyr glacial cycles, Clim. Past, 7, 1415–1425, doi:10.5194/cp-7-1415-2011, 2011.

Gates, W. L.: Modeling the Ice-Age Climate, Science, 191, 1138–1144, doi:10.1126/science.191.4232.1138, http://www.sciencemag.org/content/191/4232/1138.abstract, 1976.

Gyllencreutz, G., Mangerud, J., Svendsen, J.-I., and Lohne, Ø.: DATED—a GIS-based reconstruction and dating database of the Eurasian deglaciation, in: Applied Quaternary Research in the Central Part of Glaciated Terrain, edited by Johansson, P. and Sarala, P., pp. 113–120, Geological Survey of Finland, Espoo, Finland, 2007.

Hall, B. L., Denton, G. H., Heath, S. L., Jackson, M. S., and Koffman, T. N. B.: Accumulation and marine forcing of ice dynamics in the western Ross Sea during the last deglaciation, Nature Geoscience, 8, 625–628, http://dx.doi.org/10.1038/ngeo2478, letter, 2015.

Hargreaves, J. C., Abe-Ouchi, A., and Annan, J. D.: Linking glacial and future climates through an ensemble of GCM simulations, Clim. Past, 3, 77–87, doi:10.5194/cp-3-77-2007, http://www.clim-past.net/3/77/2007/, 2007.

Harrison, S. and Bartlein, P.: Records from the past, lessons for the future: what the palaeo-record implies about mechanisms of global change, in: The Future of the World's Climates, edited by Henderson-Sellers, A. and McGuffie, K., pp. 403–436, Elsevier, Amsterdam, the Netherlands, 2012.

Harrison, S. P., Bartlein, P. J., Izumi, K., Li, G., Annan, J., Hargreaves, J., Braconnot, P., and Kageyama, M.: Evaluation of CMIP5 palaeo-simulations to improve climate projections, Nature Clim. Change, 5, 735–743, http://dx.doi.org/10.1038/nclimate2649, review, 2015.

Hewitt, C. D. and Mitchell, J. F. B.: Radiative forcing and response of a GCM to ice age boundary conditions: cloud feedback and climate sensitivity, Clim. Dyn., 13, 821–834, doi:10.1007/s003820050199, http://dx.doi.org/10.1007/s003820050199, 1997.

Hughes, A., Mangerud, J., Gyllencreutz, R., Svendsen, J., and Lohne, O.: Evolution of the Eurasian Ice Sheets during the last deglaciation (25–10 kyr), Abstract, American Geophysical Union Fall Meeting, San Francisco, 13–19 December 2014, 2014.

Justino, F., Timmermann, A., Merkel, U., and Souza, E. P.: Synoptic Reorganization of Atmospheric Flow during the Last Glacial Maximum, J. Climate, 18, 2826–2846, doi:10.1175/JCLI3403.1, http://dx.doi.org/10.1175/JCLI3403.1, 2005.

Kim, S. J.: The effect of atmospheric CO_2 and ice sheet topography on LGM climate, Clim. Dyn., 22, 639–651, doi:10.1007/s00382-004-0412-2, 2004.

Kirtman, B., Power, S. B., Adedoyin, A. J., Boer, G. J., Bojariu, R., Camilloni, I., Doblas-Reyes, F., Fiore, A. M., Kimoto, M., Meehl, G., Prather, M., Sarr, A., Schär, C., Sutton, R., van Oldenborgh, G. J., Vecchi, G., and Wang, H.-J.: Near-term Climate Change: Projections and Predictability, in: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by Stocker, T., Qin, D., Plattner, G.-K., Tignor, M., Allen, S., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013.

Kutzbach, J. E. and Guetter, P. J.: The Influence of Changing Orbital Parameters and Surface Boundary Conditions on Climate Simulations for the Past 18 000 Years, J. Atmos. Sci., 43, 1726–1759, doi:10.1175/1520-0469(1986)043<1726:TIOCOP>2.0.CO;2, http://dx.doi.org/10.1175/1520-0469(1986)043<1726:TIOCOP>2.0.CO;2, 1986.

Lambeck, K.: Glacial rebound of the British Isles—II. A high-resolution, high-precision model, Geophys. J. Int., 115, 960–990, doi:10.1111/j.1365-246X.1993.tb01504.x, http://dx.doi.org/10.1111/j.1365-246X.1993.tb01504.x, 1993.

Lambeck, K.: Late Pleistocene and Holocene sea-level change in Greece and south-western Turkey: a separation of eustatic, isostatic and tectonic contributions, Geophys. J. Int., 122, 1022–1044, doi:10.1111/j.1365-246X.1995.tb06853.x, http://dx.doi.org/10.1111/j.1365-246X.1995.tb06853.x, 1995a.

Lambeck, K.: Late Devensian and Holocene shorelines of the British-Isles and North-Sea from models of glacio-hydro-isostatic rebound, J. Geol. Soc., 152, 437–448, 1995b.

Lambeck, K.: Limits on the areal extent of the Barents Sea ice sheet in Late Weichselian time, Global and Planetary Change, 12, 41–51, doi:10.1016/0921-8181(95)00011-9, http://www.sciencedirect.com/science/article/B6VF0-4465NNR-B/2/03bc0f6e5a85b401db47c7262a7883f0, 1996.

Lambeck, K. and Chappell, J.: Sea Level Change Through the Last Glacial Cycle, Science, 292, 679–686, doi:10.1126/science.1059549, http://www.sciencemag.org/cgi/content/abstract/292/5517/679, 2001.

Lambeck, K. and Johnston, P.: The viscosity of the mantle: evidence from analyses of glacial rebound phenomena, in: The Earth's Mantle, edited by Jackson, I., pp. 461–502, Cambridge Univ. Press, Cambridge, 1998.

Lambeck, K. and Purcell, A.: Sea-level change in the Mediterranean Sea since the LGM: model predictions for tectonically stable areas, Quat. Sci. Rev., 24, 1969–1988, doi:10.1016/j.quascirev.2004.06.025, http://www.sciencedirect.com/science/article/B6VBC-4GK1GRS-2/2/690c9f78a4240cb2a8913538411de210, 2005.

Lambeck, K., Smither, C., and Johnston, P.: Sea-level change, glacial rebound and mantle viscosity fornorthern Europe, Geophys. J. Int., 134, 102–144, doi:10.1046/j.1365-246x.1998.00541.x, http://dx.doi.org/10.1046/j.1365-246x.1998.00541.x, 1998.

Lambeck, K., Yokoyama, Y., and Purcell, T.: Into and out of the Last Glacial Maximum: sea-level change during Oxygen Isotope Stages 3 and 2, Quat. Sci. Rev., 21, 343–360, doi:10.1016/S0277-3791(01)00071-3, http://www.sciencedirect.com/science/article/B6VBC-44MX5WF-R/2/e3186b580ed7a073b386de800b896b5f, 2002.

Lambeck, K., Purcell, A., Johnston, P., Nakada, M., and Yokoyama, Y.: Water-load definition in the glacio-hydro-isostatic sea-level equation, Quat. Sci. Rev., 22, 309–318, doi:10.1016/S0277-3791(02)00142-7, http://www.sciencedirect.com/science/article/B6VBC-479K9G6-1/2/c0295808109c404ae85b5f74c636386d, 2003.

Lambeck, K., Purcell, A., Zhao, J., and Svensson, N.-O.: The Scandinavian Ice Sheet: from MIS 4 to the end of the Last Glacial Maximum, Boreas, 39, 410–435, doi:10.1111/j.1502-3885.2010.00140.x, http://dx.doi.org/10.1111/j.1502-3885.2010.00140.x, 2010.

Lambeck, K., Rouby, H., Purcell, A., Sun, Y., and Sambridge, M.: Sea level and global ice volumes from the Last Glacial Maximum to the Holocene, Proc. Nat. Acad. Sci. USA, 111, 15 296–15 303, doi:10.1073/pnas.1411762111, http://www.pnas.org/content/111/43/15296.abstract, 2014.

Mackintosh, A. N., Verleyen, E., O'Brien, P. E., White, D. A., Jones, R. S., McKay, R., Dunbar, R., Gore, D. B., Fink, D., Post, A. L., Miura, H., Leventer, A., Goodwin, I., Hodgson, D. A., Lilly, K., Crosta, X., Golledge, N. R., Wagner, B., Berg, S., van Ommen, T., Zwartz, D., Roberts, S. J., Vyverman, W., and Masse, G.: Retreat history of the East Antarctic Ice Sheet since the Last Glacial Maximum, Quat. Sci. Rev., 100, 10–30, doi:http://dx.doi.org/10.1016/j.quascirev.2013.07.024, http://www.sciencedirect.com/science/article/pii/S0277379113002898, reconstruction of Antarctic Ice Sheet Deglaciation (RAISED), 2014.

Manabe, S. and Hahn, D. G.: Simulation of the tropical climate of an ice age, J. Geophys. Res., 82, 3889–3911, doi:10.1029/JC082i027p03889, http://dx.doi.org/10.1029/JC082i027p03889, 1977.

Mangerud, J., Astakhov, V. I., Murray, A., and Svendsen, J. I.: The chronology of a large ice-dammed lake and the Barents-Kara Ice Sheet advances, Northern Russia, Global and Planetary Change, 31, 321–336, doi:10.1016/S0921-8181(01)00127-8, http://www.sciencedirect.com/science/article/pii/S0921818101001278, 2001.

Mangerud, J., Astakhov, V., and Svendsen, J.-I.: The extent of the Barents-Kara ice sheet during the Last Glacial Maximum, Quat. Sci. Rev., 21, 111–119, doi:10.1016/S0277-3791(01)00088-9, http://www.sciencedirect.com/science/article/pii/S0277379101000889, 2002.

Mangerud, J., Goehring, B. M., Lohne, Ø. S., Svendsen, J. I., and Gyllencreutz, R.: Collapse of marine-based outlet glaciers from the Scandinavian Ice Sheet, Quat. Sci. Rev., 67, 8–16, doi:10.1016/j.quascirev.2013.01.024, http://www.sciencedirect.com/science/article/pii/S0277379113000395, 2013.

MARGO Project Members: Constraints on the magnitude and patterns of ocean cooling at the Last Glacial Maximum, Nature Geoscience, 2, 127–132, doi:10.1038/ngeo411, http://dx.doi.org/10.1038/ngeo411, 2009.

Masson-Delmotte, V., Schulz, M., Abe-Ouchi, A., Beer, J., Ganopolski, J., González Rouco, J., Jansen, E., Lambeck, K., Luterbacher, J., Naish, T., Osborn, T., Otto-Bliesner, B., Quinn, T., Ramesh, R., Rojas, M., Shao, X., and Timmermann, A.: Information from paleoclimate archives, in: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by Stocker, T., Qin, D., Plattner, G.-K., Tignor, M., Allen, S., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013.

Masson-Delmotte, V., Kageyama, M., Braconnot, P., Charbit, S., Krinner, G., Ritz, C., Guilyardi, E., Jouzel, J., Abe-Ouchi, A., Crucifix, M., Gladstone, R., Hewitt, C., Kitoh, A., LeGrande, A., Marti, O., Merkel, U., Motoi, T., Ohgaito, R., Otto-Bliesner, B., Peltier, W., Ross, I., Valdes, P., Vettoretti, G., Weber, S., Wolk, F., and Yu, Y.: Past and future polar amplification of climate change: climate model intercomparisons and ice-core constraints, Clim. Dyn., 26, 513–529, doi:10.1007/s00382-005-0081-9, 2006.

Mickelson, D. and Colgan, P.: The southern Laurentide Ice Sheet in the United States: What have we learned in the last 40 years?, in: Glacial Landsystems, edited by Evans, D. and Rea, B., pp. 111–142, Erwin Arnold, London, 2003.

Nakada, M. and Lambeck, K.: Late Pleistocene and Holocene sea-level change in the Australian region and mantle rheology, Geophysical Journal, 96, 497–517, 1989.

Otto-Bliesner, B. L., Brady, E. C., Clauzet, G., Tomas, R., Levis, S., and Kothavala, Z.: Last Glacial Maximum and Holocene Climate in CCSM3, J. Climate, 19, 2526–2544, doi:10.1175/JCLI3748.1, http://dx.doi.org/10.1175/JCLI3748.1, 2006.

Paterson, W. S. B.: The Physics of Glaciers, Pergamon, Oxford, third edn., 1994.

Pausata, F. S. R., Li, C., Wettstein, J. J., Kageyama, M., and Nisancioglu, K. H.: The key role of topography in altering North Atlantic atmospheric circulation during the last glacial period, Clim. Past, 7, 1089–1101, doi:10.5194/cp-7-1089-2011, http://www.clim-past.net/7/1089/2011/, 2011.

Peltier, W. R.: The impulse response of a Maxwell Earth, Rev. Geophys. Space Phys., 12, 649–669, 1974.

Peltier, W. R.: Glacial isostatic adjustment II: the inverse problem, Geophys. J. R. astr. Soc., 46, 669–706, 1976.

Peltier, W. R.: Ice Age Paleotopography, Science, 265, 195–201, 1994.

Peltier, W. R.: On eustatic sea level history: Last Glacial Maximum to Holocene, Quat. Sci. Rev., 21, 377–396, 2002.

Peltier, W. R.: Global Glacial Isostasy and the Surface of the Ice-Age Earth: The ICE-5G(VM2) Model and GRACE, Annu. Rev. Earth Planet. Sci., 32, 111–149, 2004.

Peltier, W. R.: Closure of the budget of global sea level rise over the GRACE era: the importance and magnitudes of the required corrections for global glacial isostatic adjustment, Quat. Sci. Rev., 28, 1658–1674, doi:10.1016/j.quascirev.2009.04.004, http://www.sciencedirect.com/science/article/B6VBC-4WBR6M6-2/2/294e1b5fda5dea8507638ed522d2a75d, 2009.

Peltier, W. R. and Andrews, J. T.: Glacial isostatic adjustment I: the forward problem, Geophys. J. R. astr. Soc., 46, 605–646, 1976.

Peltier, W. R. and Drummond, R.: Rheological stratification of the lithosphere: A direct inference based upon the geodetically observed pattern of the glacial isostatic adjustment of the North American continent, Geophys. Res. Lett., 35, L16 314, doi:10.1029/2008GL034586, http://dx.doi.org/10.1029/2008GL034586, 2008.

Peltier, W. R., Argus, D. F., and Drummond, R.: Space geodesy constrains ice age terminal deglaciation: The global ICE-6G_C (VM5a) model, Journal of Geophysical Research: Solid Earth, 120, 450–487, doi:10.1002/2014JB011176, http://dx.doi.org/10.1002/2014JB011176, 2014JB011176, 2015.

Prentice, I. C., Jolly, D., and BIOME 6000 participants: Mid-Holocene and glacial-maximum vegetation geography of the northern continents and Africa, J. Biogeog., 27, 507–519, doi:10.1046/j.1365-2699.2000.00425.x, http://dx.doi.org/10.1046/j.1365-2699.2000.00425.x, 2000.

Roy, K. and Peltier, W.: Glacial isostatic adjustment, relative sea level history and mantle viscosity: reconciling relative sea level model predictions for the U.S. East coast with geological constraints, Geophys. J. Int., 201, 1156–1181, doi:10.1093/gji/ggv066, http://gji.oxfordjournals.org/content/201/2/1156.abstract, 2015.

Schmidt, G. A., Annan, J. D., Bartlein, P. J., Cook, B. I., Guilyardi, E., Hargreaves, J. C., Harrison, S. P., Kageyama, M., LeGrande, A. N., Konecky, B., Lovejoy, S., Mann, M. E., Masson-Delmotte, V., Risi, C., Thompson, D., Timmermann, A., Tremblay, L.-B., and Yiou, P.: Using palaeo-climate comparisons to constrain future projections in CMIP5, Clim. Past, 10, 221–250, doi:10.5194/cp-10-221-2014, http://www.clim-past.net/10/221/2014/, 2014.

Schmittner, A., Urban, N. M., Shakun, J. D., Mahowald, N. M., Clark, P. U., Bartlein, P. J., Mix, A. C., and Rosell-Melé, A.: Climate Sensitivity Estimated from Temperature Reconstructions of the Last Glacial Maximum, Science, 334, 1385–1388, doi:10.1126/science.1203513, http://www.sciencemag.org/content/334/6061/1385.abstract, 2011.

Shennan, I., Peltier, W., Drummond, R., and Horton, B.: Global to local scale parameters determining relative sea-level changes and the post-glacial isostatic adjustment of Great Britain, Quat. Sci. Rev., 21, 397–408, doi:10.1016/S0277-3791(01)00091-9, http://www.sciencedirect.com/science/article/pii/S0277379101000919, {EPILOG}, 2002.

Simpson, M. J. R., Milne, G. A., Huybrechts, P., and Long, A. J.: Calibrating a glaciological model of the Greenland ice sheet from the Last Glacial Maximum to present-day using field observations of relative sea level and ice extent, Quat. Sci. Rev., 28, 1631–1657, doi:10.1016/j.quascirev.2009.03.004, http://www.sciencedirect.com/science/article/B6VBC-4WN8HC6-1/2/0e7942351c3c43a713c3984299ab7664, 2009.

Svendsen, J. I., Astakhov, V. I., Bolshiyanov, D. Y., Demidov, I., Dowdeswell, J. A., Gataullin, V., Hjort, C., Hubberten, H. W., Larsen, E., Mangerud, J., Melles, M., Möller, P., Saarnisto, M., and Siegert, M. J.: Maximum extent of the Eurasian ice sheets in the Barents and Kara Sea region during the Weichselian, Boreas, 28, 234–242, doi:10.1111/j.1502-3885.1999.tb00217.x, http://dx.doi.org/10.1111/j.1502-3885.1999.tb00217.x, 1999.

Svendsen, J. I., Gataullin, V., Mangerud, J., and Polyak, L.: The glacial History of the Barents and Kara Sea Region, in: Quaternary Glaciations Extent and Chronology Part I: Europe, edited by Ehlers, J. and Gibbard, P., vol. 2, Part 1 of *Developments in Quaternary Sciences*, pp. 369–378, Elsevier, Amsterdam, the Netherlands, doi:10.1016/S1571-0866(04)80086-1, http://www.sciencedirect.com/science/article/pii/S1571086604800861, 2004.

Tarasov, L. and Peltier, W. R.: Greenland glacial history and local geodynamic consequences, Geophys. J. Int., 150, 198–229, doi:10.1046/j.1365-246X.2002.01702.x, http://dx.doi.org/10.1046/j.1365-246X.2002.01702.x, 2002.

Tarasov, L. and Peltier, W. R.: Greenland glacial history, borehole constraints, and Eemian extent, J. Geophys. Res., 108, 2143, doi:10.1029/2001JB001731, http://dx.doi.org/10.1029/2001JB001731, 2003.

Tarasov, L. and Peltier, W. R.: A geophysically constrained large ensemble analysis of the deglacial history of the North American ice-sheet complex, Quat. Sci. Rev., 23, 359–388, doi:10.1016/j.quascirev.2003.08.004, http://www.sciencedirect.com/science/article/B6VBC-4B6TXXV-2/2/960efb913c404e1d7593dc53e688e270, 2004.

Tarasov, L. and Peltier, W. R.: Arctic freshwater forcing of the Younger Dryas cold reversal, Nature, 435, 662–665, doi:10.1038/nature03617, http://dx.doi.org/10.1038/nature03617, 2005.

Tarasov, L. and Peltier, W. R.: Coevolution of continental ice cover and permafrost extent over the last glacial-interglacial cycle in North America, J. Geophys. Res., 112, doi:10.1029/2006JF000661, 2007.

Tarasov, L., Dyke, A. S., Neal, R. M., and Peltier, W. R.: A data-calibrated distribution of deglacial chronologies for the North American ice complex from glaciological modeling, Earth Planet. Sci. Lett., 315–316, 30–40, doi:10.1016/j.epsl.2011.09.010, 2012.

Taylor, K. E., Crucifix, M., Braconnot, P., Hewitt, C. D., Doutriaux, C., Broccoli, A. J., Mitchell, J. F. B., and Webb, M. J.: Estimating Shortwave Radiative Forcing and Response in Climate Models, J. Climate, 20, 2530–2543, doi:10.1175/JCLI4143.1, http://dx.doi.org/10.1175/JCLI4143.1, 2007.

Taylor, K. E., Stouffer, R. J., and Meehl, G. A.: An Overview of CMIP5 and the Experiment Design, Bull. Am. Meteorol. Soc., 93, 485–498, doi:10.1175/BAMS-D-11-00094.1, http://dx.doi.org/10.1175/BAMS-D-11-00094.1, 2012.

Toscano, M. A., Peltier, W. R., and Drummond, R.: ICE-5G and ICE-6G models of postglacial relative sea-level history applied to the Holocene coral reef record of northeastern St Croix, U. S. V. I.: investigating the influence of rotational feedback on GIA processes at tropical latitudes, Quat. Sci. Rev., 30, 3032–3042, 2011.

Tushingham, A. M. and Peltier, W. R.: ICE-3G: A new global model of late Pleistocene deglaciation based upon geophysical predictions of post-glacial relative sea level change, J. Geophys. Res., 96, 4497–4523, 1991.

Ullman, D. J., LeGrande, A. N., Carlson, A. E., Anslow, F. S., and Licciardi, J. M.: Assessing the impact of Laurentide Ice Sheet topography on glacial climate, Clim. Past, 10, 487–507, doi:10.5194/cp-10-487-2014, http://www.clim-past.net/10/487/2014/, 2014.

Vettoretti, G. and Peltier, W. R.: Last Glacial Maximum ice sheet impacts on North Atlantic climate variability: The importance of the sea ice lid, Geophys. Res. Lett., 40, 6378–6383, doi:10.1002/2013GL058486, http://dx.doi.org/10.1002/2013GL058486, 2013GL058486, 2013.

Whitehouse, P. L., Bentley, M. J., and Brocq, A. M. L.: A deglacial model for Antarctica: geological constraints and glaciological modelling as a basis for a new model of Antarctic glacial isostatic adjustment, Quat. Sci. Rev., 32, 1–24, doi:10.1016/j.quascirev.2011.11.016, http://www.sciencedirect.com/science/article/pii/S0277379111003726, 2012.

Williams, J., Barry, R. G., and Washington, W. M.: Simulation of the Atmospheric Circulation Using the NCAR Global Circulation Model with Ice Age Boundary Conditions, J. Appl. Meteorol., 13, 305–317, doi:10.1175/1520-0450(1974)013<0305:SOTACU>2.0.CO;2, http://dx.doi.org/10.1175/1520-0450(1974)013<0305:SOTACU>2.0.CO;2, 1974.

Yoshimori, M., Yokohata, T., and Abe-Ouchi, A.: A Comparison of Climate Feedback Strength between CO_2 Doubling and LGM Experiments, J. Climate, 22, 3374–3395, doi:10.1175/2009JCLI2801.1, http://dx.doi.org/10.1175/2009JCLI2801.1, 2009.

Yoshimori, M., Hargreaves, J. C., Annan, J. D., Yokohata, T., and Abe-Ouchi, A.: Dependency of Feedbacks on Forcing and Climate State in Physics Parameter Ensembles, J. Climate, 24, 6440–6455, doi:10.1175/2011JCLI3954.1, http://dx.doi.org/10.1175/2011JCLI3954.1, 2011.

Zhang, X., Lohmann, G., Knorr, G., and Purcell, C.: Abrupt glacial climate shifts controlled by ice sheet changes, Nature, advance online publication, doi:10.1038/nature13592, http://dx.doi.org/10.1038/nature13592, letter, 2014.

Table 1. The spatial domain and output variables provided by each of the individual ice sheet reconstructions, ICE-6G v.2, GLAC-1a and ANU. Latitude and longitude ranges are expressed in decimal degrees, where positive indicates north and east respectively and negative indicates south and west.

Reconstruction	Region	Latitude (°)	Longitude (°)	Resolution (°)	Variables provided
ICE-6Gv.2	global	$[-89.5, 89.5]$	$[0, 359]$	1×1	Mask(21 ka), Topo(21 ka), Bath(21 ka), Mask(0 ka), Topo(0 ka), Bath(0 ka)
GLAC-1a	North America	$[34.75, 84.25]$	$[187.5, 354.5]$	1×0.5	Thick(21 ka), topo(21 ka)
	Eurasia	$[48.125, 83.125]$	$[-12.75, 119.25]$ ~~$[347.25, 479.25]$~~	0.5×0.25	
ANU	Antarctica	$[-89.5, -61.5]$	$[-179, 180]$	1×1	ΔThick(21 ka), RSL(21 ka)
	Eurasia	$[50.25, 83]$	$[0, 115.5]$	0.5×0.25	
	North America	$[38, 84.5]$	$[-139, -7]$	0.5×0.25	
	Britain	$[52, 59]$	$[-10, 4]$	1×1	ΔThick(20 ka)

Table 2. Implied changes (Last Glacial Maximum−present)~~Implied changes~~ in ice volume for the Laurentide, Eurasian and Antarctic Ice Sheets, expressed in terms of impact on eustatic sea level (in m). The impact of eustatic sea level is inferred by assuming no change in ocean area compared to today (assumed ocean area: $360\,768\,576\,\mathrm{km^2}$), and using densities for ice and water of 910 and $1028\,\mathrm{kg\,m^{-3}}$ respectively. Results are shown for the three individual reconstructions (ICE-6Gv.2, GLAC-1a, ANU) and for the composite CMIP5/PMIP3 ice sheets, and compared to the implied changes for the ice sheets used in the Last Glacial Maximum simulations run in the first and second phases of the Palaeoclimate Modelling Intercomparison Project (PMIP1, PMIP2).

	North America	Eurasia	Antarctica	Total
ICE-6Gv.2	76.8	17.5	15.6	113.0
GLAC-1a	76.6	14.0	Not reconstructed	Not available
ANU	82.5	18.2	29.0	130.0
CMIP5/PMIP3 composite	78.6	16.6	22.3	121.5
PMIP1(ICE-4G)	60.5	29.1	21.7	117.8
PMIP2(ICE-5Gv1.1)	74.6	20.3	17.3	112.2

Table 3. Change in radiative forcing ($\mathrm{W\,m^{-2}}$) associated with changes in ice sheet and implied changes in land-sea geography, calculated for the CMIP5/PMIP3 composite and the PMIP2 ice sheets respectively. The resulting change in global annual mean surface air temperature ($^{\circ}\mathrm{C}$) is shown in the last column. The error is calculated as the difference between the estimates obtained while using the present day climate as a reference or the glacial climate as a reference in the partial-radiative perturbation calculation. Note that the values given for the PMIP2 ice sheet are slightly different from those given in Braconnot et al. (2012) because of corrections made subsequent to the publication of that paper. Values given here may also differ slightly from published results of individual models where either a different method or a different time window was used for the calculation.~~Change in radiative forcing associated with changes in ice sheet and implied changes in land-sea geography, calculated for the CMIP5/PMIP3 composite and the PMIP2 ice sheets respectively. The resulting change in temperature (Δtas) is also shown. The error is calculated as the difference between the estimates obtained while using the present day climate as a reference or the glacial climate as a reference in the partial-radiative perturbation calculation. Note that the values given for the PMIP2 ice sheet are slightly different from those given in Braconnot et al. (2012) because of corrections made subsequent to the publication of that paper. Values given here may also differ slightly from published results of individual models where either a different method or a different time window was used for the calculation.~~

Climate model	Ice sheet	Ice sheet change ($\mathrm{W\,m^{-2}}$)	Land-sea change ($\mathrm{W\,m^{-2}}$)	Combined change ($\mathrm{W\,m^{-2}}$)	Temperature change~~Δtas~~ ($^{\circ}\mathrm{C}$)
CCSM4	CMIP5/PMIP3	-2.47 ± 0.10	-1.33 ± 0.00	-3.79 ± 0.10	-4.91
IPSL-CM5A-LR	CMIP5/PMIP3	-3.11 ± 0.15	-1.79 ± 0.05	-4.90 ± 0.20	-4.60
MIROC-ESM	CMIP5/PMIP3	-3.45 ± 0.51	-1.75 ± 0.19	-5.20 ± 0.70	-5.00
MPI-ESM-P	CMIP5/PMIP3	-3.49 ± 0.62	-1.08 ± 0.06	-4.57 ± 0.68	-4.41
MRI-CGCM3	CMIP5/PMIP3	-1.85 ± 0.10	-1.77 ± 0.02	-3.62 ± 0.12	-4.68
CCSM3	PMIP2	-1.85 ± 0.12	-0.88 ± 0.00	-2.72 ± 0.12	-4.51
CNRM	PMIP2	-2.25 ± 0.32	-0.74 ± 0.01	-2.98 ± 0.32	-3.05
HadCM3M2_oa	PMIP2	-2.55 ± 0.40	-1.19 ± 0.11	-3.73 ± 0.51	-5.11
HadCM3M2_oavM3M2_oa	PMIP2	-2.72 ± 0.45	-1.27 ± 0.12	-3.98 ± 0.57	-5.86
IPSL-CM4	PMIP2	-2.43 ± 0.11	-1.17 ± 0.03	-3.60 ± 0.13	-3.79
MIROC3.2	PMIP2	-2.76 ± 0.54	-0.78 ± 0.12	-3.54 ± 0.66	-3.70

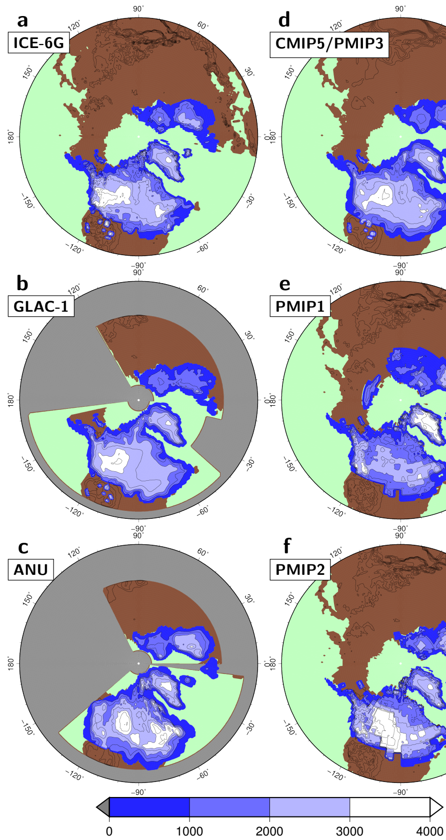

Figure 1. Surface elevation (m) at the Last Glacial Maximum (LGM) Northern Hemisphere ice sheets from the **(a)** ICE-6Gv.2, **(b)** GLAC-1a and **(c)** ANU reconstructions, and for **(d)** the CMIP5/PMIP3 composite compared to the ice sheets used in **(e)** PMIP1 and **(f)** PMIP2.

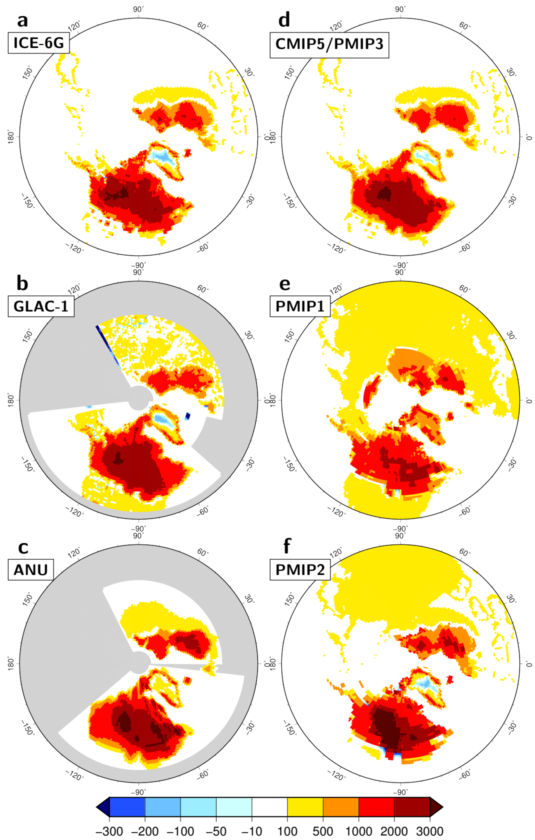

Figure 2. Difference in surface elevation (m) of the Northern Hemisphere ice sheets at the LGM compared to the present-day from the **(a)** ICE-6Gv.2, **(b)** GLAC-1a and **(c)** ANU reconstructions, and for **(d)** the CMIP5/PMIP3 composite compared to the ice sheets used in **(e)** PMIP1 and **(f)** PMIP2. The region shown is between 40 and 90° N.

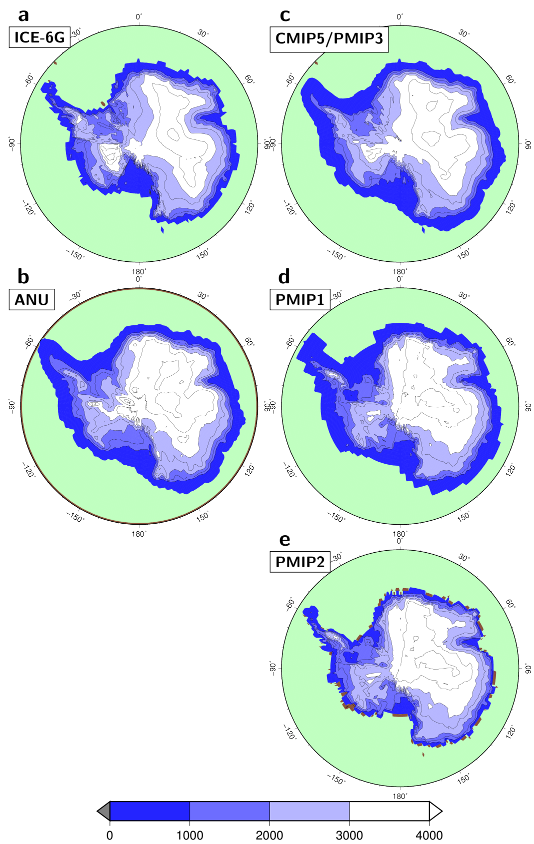

Figure 3. Surface elevation (m) of Antarctica at the LGM from the **(a)** ICE-6Gv.2, **(b)** ANU reconstructions, and for **(c)** the CMIP5/PMIP3 composite compared to the ice sheets used in **(d)** PMIP1 and **(e)** PMIP2. The GLAC-1a reconstruction for Antarctica is identical to that of ICE-6G, and is therefore not shown.

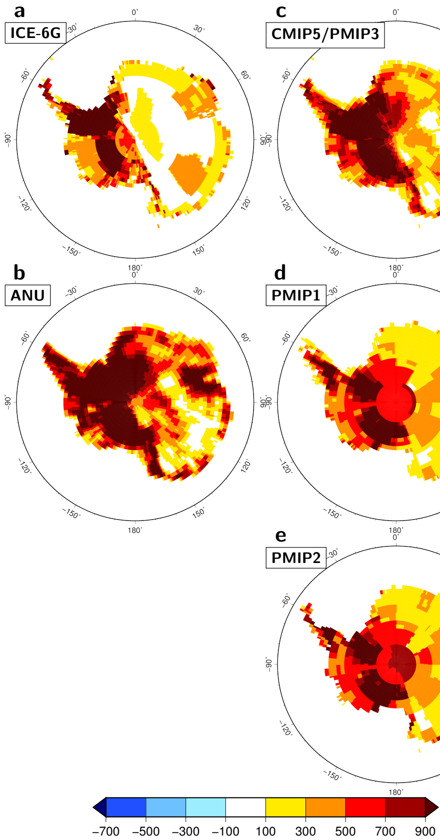

Figure 4. Difference in surface elevation (m) of Antarctica at the LGM compared to the present-day from the **(a)** ICE-6Gv.2, **(b)** ANU reconstructions, and for **(c)** the CMIP5/PMIP3 composite compared to the ice sheets used in **(d)** PMIP1 and **(e)** PMIP2. The GLAC-1a reconstruction for Antarctica is identical to that of ICE-6G, and is therefore not shown.

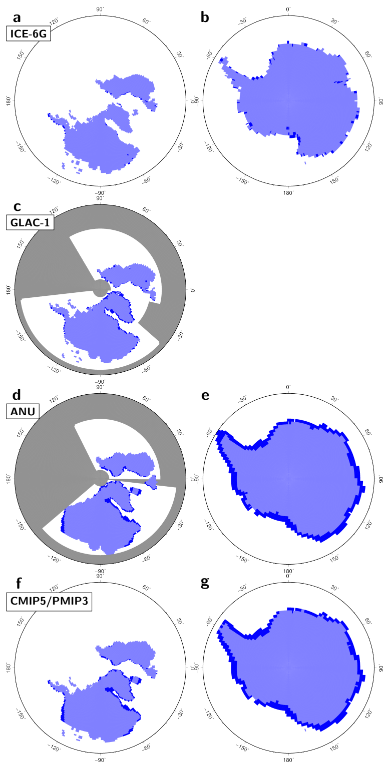

Figure 5. Ice/shelf extent at the LGM from the ice/shelf masks for the Northern Hemisphere derived from ICE-6Gv.2 for **(a)** the Northern Hemisphere and **(b)** Antarctica, from GLAC-1a **(c)** for the Northern Hemisphere, and from ANU for **(d)** the Northern Hemisphere and **(e)** Antarctica. The GLAC-1a reconstruction for Antarctica is identical to that of ICE-6Gv.2, and is therefore not shown. These reconstructed masks can be compared with the CMIP5/PMIP3 mask for **(f)** the Northern Hemisphere and **(g)** Antarctica. Cyan, blue and white areas indicate the grounded-ice, floating-ice and ice-free region, respectively.

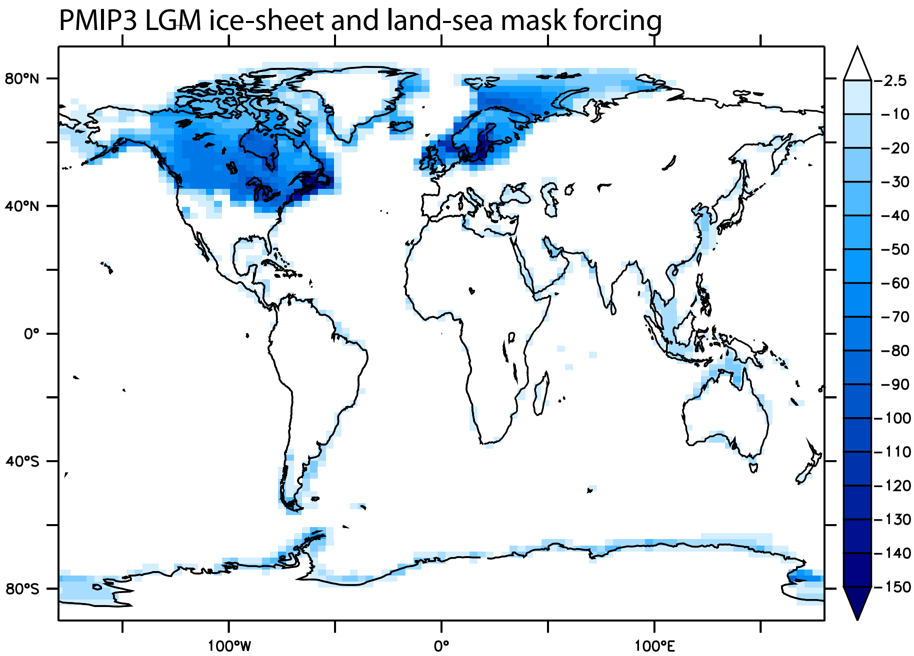

Figure 6. Estimation of the difference in radiative forcing ($W\,m^{-2}$) ~~and feedbacks~~ at the LGM compared with pre-industrial conditions caused by imposition of the CMIP5/PMIP3 ice sheet and the change in the land-sea mask. The map is a composite of the results from five ocean-atmosphere models showing the spatial patterns of the change in total forcing associated with the expanded Northern Hemisphere ice sheets at the LGM and with the increase of land area due to lowered sea level.

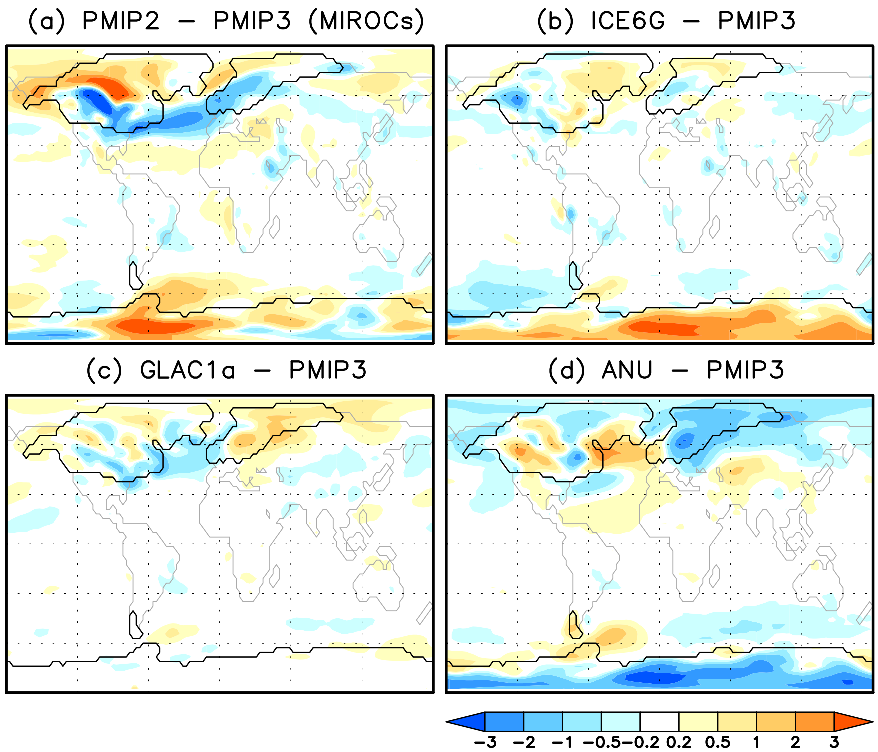

Figure 7. Differences in mean annual temperature (°C) caused by using different ice sheet configurations from the CMIP5/PMIP3 composite ice sheet in simulations made with the MIROC slab ocean model. The individual ice sheet configurations are **(a)** PMIP2, **(b)** ICE-6G v.2, **(c)** GLAC-1a, and **(d)** ANU ice sheets, where each is referenced to the CMIP5/PMIP3 composite ice sheet. The land mask ($> 50\,\%$ land) is shown in grey, the ice margin ($> 50\,\%$ ice) is shown in black on all four plots. ~~Impact of ice sheet choice on mean annual temperature (MAT) in simulations made with the MIROC slab ocean model. The plots show **(a)** MAT in the simulation with the CMIP5/PMIP3 composite ice sheet (CMIP5/PMIP3), **(b)** differences between this reference simulation and simulations made with **(b)** ICE-6Gv.2, **(c)** GLAC-1a, and **(d)** ANU. The land mask (> 50 % land) is shown in grey, the ice margin (> 50 % ice) is shown in black on all four plots.~~

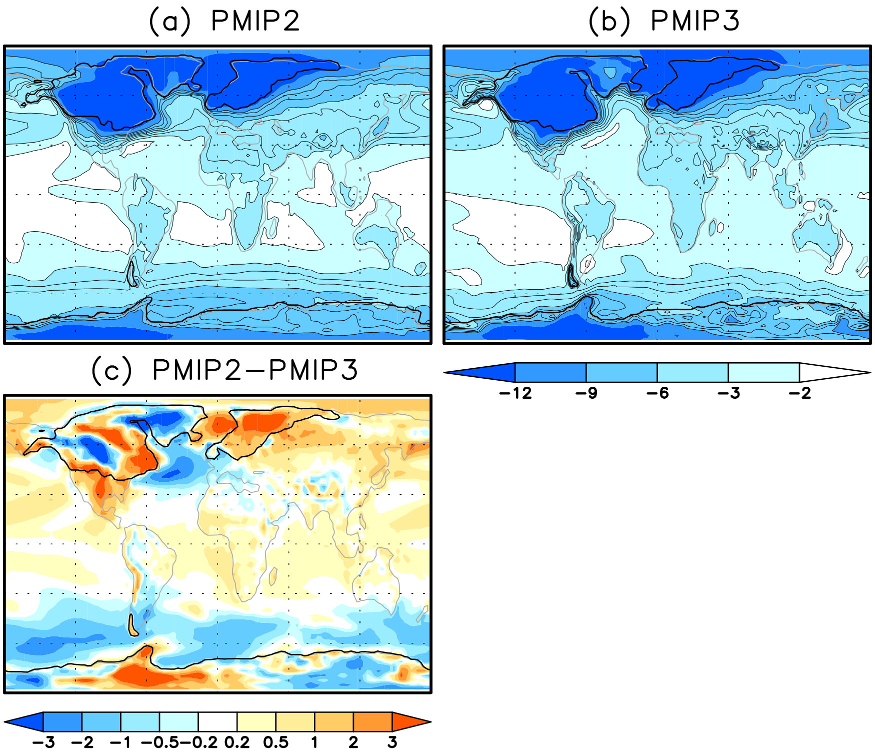

Figure 8. Change in mean annual temperature (°C~~MAT~~) in the **(a)** PMIP2 and **(b)** CMIP5/PMIP3 coupled ocean-atmosphere simulations. Each of these plots is an ensemble average of all the LGM simulations in PMIP2 and CMIP5/PMIP3 respectively. The difference between the ensemble mean results for the two generations of experiments is shown in plot **(c)**. The land mask ($>50\,\%$ land) is shown in grey, the ice margin ($>50\,\%$ ice) is shown in black on all plots. Contour lines in **(a)** and **(b)** are at $1\,^{\circ}\mathrm{C}$ intervals to $-9\,^{\circ}\mathrm{C}$; temperature differences $>-9\,^{\circ}\mathrm{C}$ are not differentiated.~~The land and ice masks are the same as Fig. 7. Contour lines are also illustrated in **(a,** b). The contour interval is 1 °C where the temperature is higher than −9 °C.~~

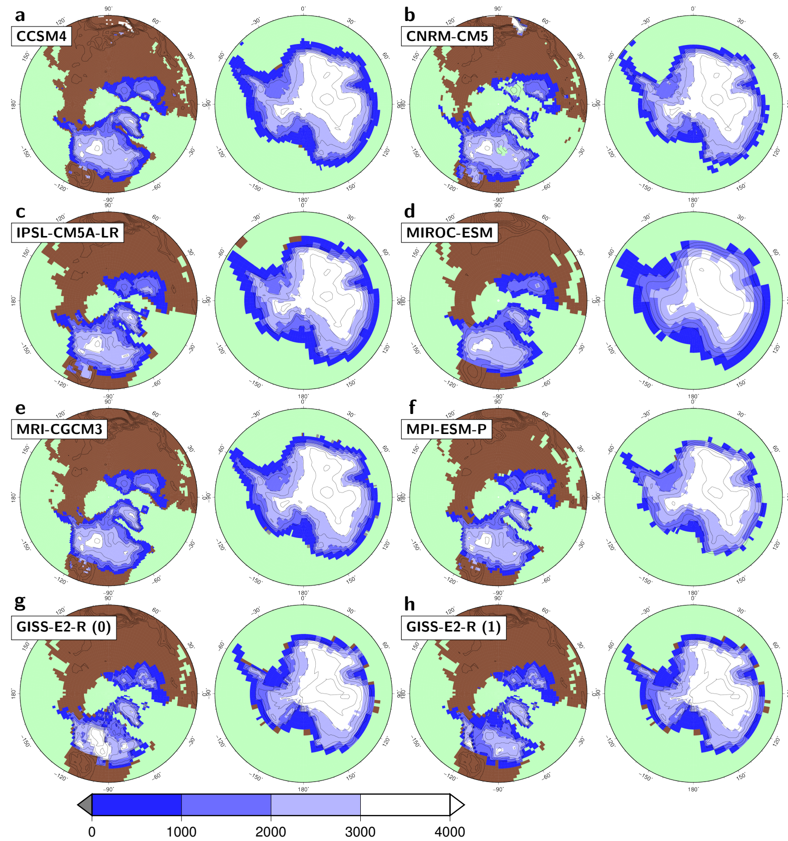

Figure 9. Implementation of the CMIP5/PMIP3 composite ice sheet in individual models. The plots show the surface elevation (m) as implemented in each model, and thus reveal that there are small differences in prescribed ice sheet between models because of differences in e.g. model type and resolution.~~Implementation of the CMIP5/PMIP3 composite ice sheet in individual models. These plots show that there are small differences in prescribed ice sheet between models because of differences in e.g. model type and resolution.~~