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Interactive comment on "A model-data comparison of the Last Glacial Maximum surface temperature changes" *by* Akil Hossain et al.

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Answer to reviewers' comments: A model-data comparison of the Last Glacial Maximum surface temperature changes

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General remarks

We are very thankful to the editor and reviewers for the effort and time dedicated to the reviewing of our manuscript and for the helpful reviews. In order to address all

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Discussion paper

the concerns raised by the reviewers we have significantly restructured the manuscript and few new section. In this document, we supply detailed responses to all comments, suggestions and notes made by the two reviewers. We hope that the applied revisions are to the satisfaction of the reviewers and the editor.

Reviewer #2: Comment R2.1

My first point concerns the structure of the paper which is not appropriate as it is. In draft I have, a lot of things are confusing (for ex., figures 6 et 7 are not mentioned and discussed in the text; it's quite the same for the figure with PMIP and IPSL models even if I have downloaded the corrected version).

AC(Author Comment): Structure of the paper is changed and discuss in detailed at the Comment 2.2. These issue with figure has been revised and solved.

Author's changes in manuscript: Figure 6 is now mentioned in the section 3.2.1 and Figure 7 is removed according to our new structure. Figure with PMIP and IPSL models also now mentioned in the section 3.2.1.

Comment R2.2

The structure of the results and discussion parts is not clear and not easy to follow. I strongly recommend to group the results and the discussion in the same part. I propose to restructure it as follow: 1. model comparison 1.1 LIS simulations 1.2 COSMOS, PMIP3, IPSL comparison 2 data-model comparison: 2.1 terrestrial temperatures changes 2.2 SSTs changes (including seasonality and depth)

AC: By considering this suggestion our result and discussion part is restructured as follows:

3.1 Data Model Comparison: COSMOS LIS reconstructions 3.1.1 Sea surface temperature changes 3.1.2 Proxy-specific comparison of SST Annual Mean 3.1.3 Seasonality of the recorder system 3.1.4 Land Surface temperature changes 3.1.5 Mean temperature of coldest and warmest month 3.2 Data Model Comparison: PMIP3 models 3.2.1

Sea surface temperature changes 3.2.2 Land Surface temperature changes

Considering habitat depth of the planktonic organisms make our manuscript more complicated and there are many debates about habitat depth of the organisms, therefore, according to our new structure, we have removed the habitat depth analysis of proxies. So this section is no more in the manuscript.

Author's changes in manuscript:

Removed–

L21: habitat depths and L23: habitat depth and L55: as well as habitat depth L62-65: Thereby, two parameters might influence the estimations of LGM SST anomalies: changes in bloom seasons (Rosell-Melé et al., 1995; Sikes et al., 1997; Barker et al., 2005; Haug et al., 2005; Davis and Brewer, 2009; Fraile et al., 2009; Kim et al., 2015), and changes in habitat depth of different species (Nürnberg et al., 1995; Bentaleb et al., 1999; Barker et al., 2005; de Vernal et al., 2006; Kim et al., 2015).

L66: water depths and L70: habitat depth and L72: and water depths L163: and depth L255-88: 3.5 Habitat depth of the recorder system

In this study, the observational data of MARGO project is composed of different Planktonic organisms which are however known to be able to move in the different water column (e.g. Conte et al., 2006). In order to observe whether deeper layers in the model would be in better agreement with the temperature reconstruction than surface, the model for different layers of the upper 183 m of the ocean were compared to the proxy records (Fig. 5a). Layers below these depths can be ignored, since alkenone-producing organisms require sun-light for photosynthesis.

From the Fig. 3, it can be observed that most of the core sites in the North Atlantic are in best agreement with the surface layers (0 to 37 m) and in the Southern Hemisphere with subsurface layers (between 70 to 183 m). For dinoflagellates, most core point of it also agree with subsurface layer. For the Mg/Ca ratio, the same upper layers are also considered, but from the Fig. 5a it can be seen that a big part of the record best agree with the upper level of the ocean although a few cores in the North Atlantic from subsurface layers. For alkenones, a big part of the records best agree with the deeper level of the ocean, between 70 and 183 m (Fig. 5a). Rest of the cores do not show any clear evidence for a preferred ocean layer (Fig. 5a).

Investigations of foraminiferal Mg/Ca distributions in the Atlantic, Pacific, and Indian Oceans have found that 75–100% of foraminifera species live between 0 to 40 m water depths (van Donk 1977; Kim et al., 2015). Alkenone-based temperatures record do not always precisely represent the SST, because of ambiguities due to the habitat depth of alkenone-producing organisoms (Ohkouchi et al. 1999; Lee and Schneider 2005). The planktonic foraminifera live over a range of depths, mostly between about 75 and 250 m water depth (de Vernal et al., 2006).

The correlation between the reconstructed and simulated anomalies has been also increased significantly for best fit depth. A higher correlation has been found for the best fit depth (R = 0.65) than the annual mean (R = 0.51) in case of Mg/Ca (Table 1 and Table 3). Foraminifera show also significantly high correlation for depth (R = 0.54) which is also higher than annual (R = 0.43). A positive correlation have been found for the best fit depth in case of dinoflagellates and alkenones (dinoflagellates, R = 0.16; alkenones, R = 0.36) (Table 3) where they show negative correlation for annual mean (Table 1).

If we consider best fit seasons and depths together at the same time at a specific data point in the model simulations, the mismatch between the climate simulation of the model and different proxy records has been decreased and correlation coefficient has been also increased significantly (Fig.: S4; Table S5). Planktonic foraminifera inhabit a wide range of the water column and also show variability in their seasonal abundance. The average proxy signal in sedimentary foraminifera is weighted towards conditions at the season and depth of calcification rather than reflecting annual mean surface conditions (Jonkers and Kučera, 2017).

L309: habitat depth,. . .. . . , and habitat depth-seasonality together (new L275) L319: and depth (new L285) L324: water depth and (new L290) L360-78: 4.3 Habitat depth biases

Changes in the habitat depth of the SST over the LGM result in deviations between model simulations and proxy records. Such changes in recording season and habitat depth could have been caused by changes in insolation over the LGM or by related changes in the nutrient distribution and ocean temperature that the individual proxies are exposed to (Lohmann et al., 2013). Comparing the reconstructed LGM temperature trends at model levels in the upper 183 m does not remove the discrepancy between models and proxies. In comparison with the previous study indicates the planktonic foraminifera live over a range of depths, mostly between about 75 and 250 m water depth (de Vernal et al., 2006). A recent study (Kim et al., 2015) suggested that foraminiferal Mg/Ca record temperatures at depths of 0-40 m in the water column. Alkenone concentrations were high at the subsurface water column of the central Pacific Ocean (Lee and Schneider, 2005) agree with model simulation. The majority species of the planktonic foraminifer assemblages in polar waters inhabits subsurface waters (Bé and Tolderlund, 1971) and may find below the thermocline as it is frequently the case in the Arctic, subarctic and other stratified waters where it occurs along or below the halocline (Kohfeld et al., 1996; de Vernal et al., 2002; Hillaire-Marcel et al., 2004; de Vernal et al., 2006). Planktonic foraminifera normally migrate vertically throughout their life cycle, forming calcite at deeper layers as they mature. This temperature/depth migration results in heterogeneity of Mg/Ca ratios within tests of individual foraminifera (Nürnberg, 1995; Jha and Elderfield, 2000; Elderfield and Ganssen, 2000; Benway et al., 2003). It has been observed that various planktonic species add a calcite crust in colder, deeper water immediately prior to reproduction (Barker et al., 2005). Many species of planktonic foraminifera live at depths greater than 50m (Erez and Honjo, 1981; Deuser and Ross, 1989; Anand et al., 2003) which agree with the studied model simulation.

L424: and different water depths at which the recording organisms may have lived L429-32: Comparing the reconstructed LGM temperature anomalies with the model levels of the upper 183 m does not remove the discrepancy between models and proxies. For Mg/Ca ratios, a large number of records fit best with the model surface layer. In case of the remaining three proxies, the best-fit agreement is found in the subsurface layer. Thus, we find mostly the highest agreement between proxy-record and simulated temperature anomalies in the subsurface layer depth.

Added–

L62-65: Thereby, changes in bloom seasons might influence the estimations of LGM SST anomalies (Rosell-Melé et al., 1995; Sikes et al., 1997; Barker et al., 2005; Haug et al., 2005; Davis and Brewer, 2009; Fraile et al., 2009; Kim et al., 2015).

L243: 3.1.5 Mean temperature of coldest and warmest month

According to Bartlein et al. (2011), July temperature in the northern hemisphere (southern hemisphere - December) has been combined with reconstructions of mean temperature of the warmest month (MTWA). Similarly, December temperature in the northern hemisphere (southern hemisphere - July) has been combined with reconstructions of mean temperature of the coldest month (MTCO) (Fig. S3, see also Bartlein et al., 2011).

During the LGM, Africa show warmer (1 to 4°C) than today in the reconstruction of MTWA (Fig. S3, see also Wu et al. 2007). A few sites in the northern hemisphere especially in the Alaska, reconstruction of warmer conditions as shown by seasonal temperature variable MTWA and similar or slightly warmer than today is registered chiefly in MTCO (Fig. S3) (Bartlein et al., 2011). The LIS was large enough to cause atmospheric circulation pattern reorganization. This reorganization could have originated in more southerly landward flow into Alaska, that would have produced advective warming in this region year-round (Bartlein et al., 2011). In general, the summer temperatures changes as represented by MTWA (Fig. S3) are smaller than the winter temperatures changes as represented by MTCO (Fig. S3, see also Bartlein et al., 2011).

For a comparison with proxy data, the warmest and coldest months of the model results have been compared with the seasonal temperature variables MTWA and MTCO. For MTWA, the highest correlation coefficient and lowest deviations are found for the LGMctl (R = 0.50, RMSE = 6.5‰ and Ice6g_LIS (R = 0.50, RMSE = 6.5‰ ice-sheet reconstruction and the lowest correlation coefficient and largest deviations for the Gowan_NAIS (R = 0.44, RMSE = 6.3‰ (Fig. 5). Similarly, for MTCO, the highest correlation coefficient and lowest deviations are also found for the LGMctl (R = 0.46) and Ice6g_LIS (R = 0.46) and the lowest correlation coefficient for the Gowan_NAIS (R = 0.43) (Table 3). Overall, the correlation coefficient value for warmest and coldest months of the model has been increased than the model Annual mean value (Table 3).

L291: 3.2.2 Land Surface temperature changes

The annual mean SAT of PMIP3 LGM climate is on average 4.5 oC colder than the PI climate and CNRM is comparatively warmer (annual mean temperature -2.6 oC) than other models. PMIP3 model results have been compared with the LGM continental temperature reconstruction by Bartlein et al. (2011). The reconstructions show year-round cooling during the LGM over the continents except a few sites in Alaska (Fig. 7) (Bartlein et al., 2011). Similar as SST reconstructions, among the eight PMIP3 model, IPSL-CM5A-LR (R = 0.27, RMSE = 3.3‰ shows the highest correlation (Table S5), although most of the model show low correlation coefficient with the reconstructed data-set. MTWA (highest R is 0.53) show higher correlation than MAT and MTCO (highest R is 0.27 and 0.48). Overall, the correlation between model and data has been increased for MTWA and MTCO than the model Annual mean value (Table S5).

Comment R2.3

The comparison with the terrestrial temperature changes is an important point given that if I remember well, PMIP models often underestimated the LGM cooling. SO I would like to add this figure not in the supplementary material as it is in the current form but in the text to support the discussion. May be you can also compare the seasonal parameters (temperature of the coldest and warmest month) simulated by COSMOS with MTCO and MTWA inferred from pollen.

AC: This figure of the comparison with the terrestrial temperature changes is shifted to the main script. A subsection of seasonal parameters comparison also added to the manuscript.

Author's changes in manuscript: Fig. S2 now Fig.5 See Comments 2.2 for the Paragraph "3.1.5 Mean temperature of coldest and warmest month"

Comment R2.4

My second point concerns the originality of this paper. The objective and the questions of your paper need to be better justified. There is a lot of simulations on the LGM as this period has been chosen by the PMIP modelers; therefore we need to better understand what are your questions, and what is new compared to previous studies. I have the same feeling for data-model comparisons: they are a lot of, and the Bartlein and Margo datasets are not new: could you better clarify the originality of your approach and of your results?

AC: Our submitted manuscript is examined the uncertainties in SAT and SST of different ice sheets reconstructions and the PMIP3 models which is unique in its kind of research.

The main objectives of our paper: i) to assess the different LIS reconstructions and PMIP3 models and ii) to assess biases in the recording of different proxies. We have compared the reconstructions of LGM temperature on land and in the ocean with the different ice sheets reconstructions and the PMIP3 models. We have also assess the potential recording biases in the proxy data and found that particularly in the marine realm there is considerable mismatch between the data and the models and these are due to seasonal recording biases in the proxies.

There are some more datasets for temperature reconstruction but MARGO and Bartlein dataset are much intense with large coverage area.

Author's changes in manuscript: No change

Comment R2.5

Moreover, several points of the discussion must be discussed more in depth or are lacking (see below). Other points:-Title: should be more informative

AC: After discussing with the co-authors, we have decided that the title is appropriate according to our content and not to change it.

Author's changes in manuscript: No change Comment R2.6

- Abstract : must be more precise (key results, conclusions)

AC: We have make a revision on abstract.

Author's changes in manuscript: Abstract Over the Last Glacial Maximum (LGM, ∼21ka BP), the presence of vast Northern Hemisphere ice-sheets caused abrupt changes in surface topography and background climatic state. While the ice-sheet extent is well known, several conflicting ice-sheet topography reconstructions suggest that there is uncertainty in this boundary condition. The terrestrial and sea surface temperature (SST) of the LGM as simulated with six different Laurentide Ice Sheet (LIS) reconstructions in a fully coupled Earth System Model (COSMOS) have been compared with the subfossil pollen and marine temperature proxies reconstruction. The terrestrial reconstruction shows a similar pattern and in good agreement with model data. The SST proxy dataset comprises a global compilation of planktonic foraminifera, diatoms, radiolarian, dinocyst, alkenones and planktonic foraminifera Mg/Ca-derived SST estimates. Significant mismatches between modeled and reconstructed SST have been observed. Among the six LIS reconstructions, simulation using Tarasov's LIS reconstruction shows the highest correlation with reconstructed terrestrial and SST. Dinocyst-based SST records are much warmer than reconstructed by other proxies as well as Pre-industrial (PI) temperature. However, there are large discrepancies between model and temperature recorded by different proxies. In the most densely sampled Nordic Sea, the reconstructed LGM SST have large uncertainties. Eight different PMIP3 models also compared with temperature proxies reconstruction which show mismatches with the the proxy records might be due to misinterpreted and/or biased proxy records. Therefore, it has been speculated that considering different growing seasons of the planktonic organisms used for SST reconstruction could provide a better agreement with model results on a regional scale. Moreover, it can reduce model-data misfits. It is found that shifting in the living season can remove parts of the observed model-data mismatches in SST anomalies.

Comment R2.7

- Introduction : -line 32 : correct “Projection” with Project”; more refs are needed for PMIP (Joussaume et al...);

AC: This term has been corrected and reference has been added.

Author’s changes in manuscript: Paleoclimate Modeling Intercomparison Project (PMIP). Joussaume and Taylor, 1995; Braconnot et al., 2007, 2012; Kageyama et al., 2006, 2013, Wang et al., 2013

Comment R2.8

-Line 36: You state that “Previous studies proposed that these northern hemisphere ice sheets, especially the North American Laurentide ice sheet (LIS), are of crucial importance on modulating glacial climate”: could you briefly precise its role on glacial climate?

AC: The role of LIS on glacial climate is shortly added to the manuscript.

Author’s changes in manuscript: L36: Changes in the ice sheet height can influence on the ocean circulation and even the background climate (Zhang et al., 2014). The greater topography of the LISs forces a relatively stronger AMOC (Zhang et al., 2014).

Comment R2.9

-Line 51 and 110 : Please avoid to use the term “plant macrofossils”: the annual temperature is mainly based on pollen data through transfer function (sites with macrofossils data are very few for the LGM and its complex to provide robust quantitative temperature estimates from macrofossils alone).

AC: This term has been removed from the manuscript.

Author’s changes in manuscript: L51 and L110: “plant macrofossils” is romeved (new L52 and L109) Comment R2.10

-Line 63: I don’t think the ref Davis and Brewer (2009) is appropriate here, they don’t talk about the bloom season; AC: Yes, I partly agree with you as it doesn’t mentioned directly bloom season but they used a palaeoclimate record to determine orbital forcing is biased towards the summer season and high latitudes.

Author’s changes in manuscript: L64: ‘Davis and Brewer, 2009’ reference is removed. Comment R2.11

-Line 76: a ref is needed for the model COSMOS

AC: A reference Zhang et al., 2013 has been added. Author’s changes in manuscript: (Zhang et al., 2013) Comment R2.12

- Material and methods - a table with the different LIS reconstructions will be welcome

AC: A table with the different LIS reconstructions and their references has been added.

Author’s changes in manuscript: Table S1: LIS reconstructions used in this study.

Comment R2.13

-line 111: you mention the different climate parameters reconstructed from pollen data in the Bartlein et al synthesis (MTWA, GDD5 MTCO and MAT). As you only use in your paper the annual temperature reconstruction, it’s not necessary to mention the others climate parameters. In contrast, you can write few words on the method used (Mat, transfer function or inverse modelling). I strongly recommend to also compare the seasonal parameters (temperature of the coldest and warmest month) simulated by COSMOS with MTCO and MTWA inferred from pollen. AC: Considering this comment, the seasonal parameters (temperature of the coldest and warmest month) simulated by COSMOS and PMIP3 model have been compared with MTCO and MTWA inferred from pollen. A subsection of seasonal parameters comparison added to the manuscript.

Author’s changes in manuscript: See Comment R2.2

Comment R2.14

-line 136: avoid words as Âń proxy-derived observational data Âż; the temperature is reconstructed from proxies, it’s not observational data. Use instead proxy-inferred temperature; there is a lot of such approximations in the text, please correct it everywhere.

AC: This term has been checked and revised in the manuscript.

Author’s changes in manuscript: L136, 159 and 432: proxy-inferred temperature data

Comment R2.15

- Results: not appropriate as it is. I also strongly recommend to group the results and the discussion in the same part to avoid to be lost. -line 225: you state that In the North Atlantic Ocean, the best agreement of planktonic foraminifera, dinoflagellates, and alkenones is found for local summer. I don’t agree with you, I don’t see it on the figure.

AC: There was a fault in the color bar of the Figure 4 (a), where JJA is shown as MAM and vice versa. However, in the North Atlantic Ocean, best agreement for organisms is not very clear but highest amount of data was found representing summer temperature.

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Author’s changes in manuscript: The color bar of the Figure 4 (a) is changed. Comment R2.16

-line 259: how did you define the different layers? Arbitrary or statistical threshold? -line 264: why 37m? not 27 or 47as in the caption?

AC: Considering habitat depth of the planktonic organisms make our manuscript more complicated and there are many debates about habitat depth of the organisms, therefore, according to our new structure, we have removed the habitat depth analysis of proxies. So this section is no more in the manuscript.

Author’s changes in manuscript: L255-288 is removed from the manuscript.

Comment R2.17

-line 305: what do you mean by “Instead, the ensemble median (Fig. 2a) typically displays the common signal. In this case, it is the mean value of the fourth and fifth ensemble member out of eight models which are ordered according to ranked values”? Really not clear!

AC: As mentioned earlier in the manuscript, we have used eight PMIP3 models and due to space limitations, all individual model anomalies and their agreement/disagreement with the proxy-derived SST trends is not shown. Instead of that we have showed the ensemble median of them. First, we have ordered the models according to their ranked values. Then, we calculate the mean value of the fourth and fifth ensemble member out of eight models which represent the the ensemble median.

Author’s changes in manuscript: Instead, the ensemble median of them is shown here (Fig. 2a) which typically displays the common signal.

Comment R2.18

- Discussion is too short, it must be clarified according to the objectives of the paper and the results (which also need to be more precise). A comparison between these results and previous LGM simulations is required and must be discussed. A comparison with the CLIMAP values and other studies will also be welcome. A more in depth discussion of the agreement between terrestrial pollen-based temperature and model output is also needed as I have in mind that usually the models underestimates the values inferred from the data as it was the case in the previous PIMP simulations.

AC: Discussion is revised and mentioned at the Response letter to the Reviewer 1.

Author's changes in manuscript: See Response letter to the Reviewer 1 L302-09: The glacial ocean state has been under debate since the first reconstruction of the LGM sea surface temperatures and sea ice coverage by the CLIMAP project (CLIMAP Project Members, 1976). The SST reconstruction by the MARGO project (Waelbroeck et al., 2009) compared to CLIMAP indicates a more pronounced cooling in the eastern mid-latitude of the North Atlantic than in the western basin, a 1-3 oC cooling in the western Pacific warm pool (Fig. 1), as well as ice-free conditions in the Nordic Sea during glacial summer. According to MARGO study, in all the ocean basins, there is a large longitudinal gradient in LGM SST anomalies which are absent in the most of atmosphere-ocean coupled simulations of the PMIP2 project (Waelbroeck et al., 2009). A rather uniform SST cooling during the LGM in the range of 2-4 oC has been found (Fig. 1).

Comment R2.19

-in the 4.3 part, you discuss foraminifers, alkenones and MGCa ratio, but nothing is written about the dinos. I'm sure that a lot of papers are available. - Data model discrepancies can also been explained by the proxy itself or by the method (transfer function...); this point is important and need to be discussed - Line 410: You state that the proxy records used in most of the studies are more often located in coastal areas. I don't agree with you: Dino and forams records are not only located in coastal areas. - Figures : the order of each figure must be carefully checked in the text. The colors of the figures 5 a and 7a must be changed for more clarity.

AC: Same as comment R1.16.

Author’s changes in manuscript: L360-412 is removed from the manuscript.

Please also note the supplement to this comment:
https://www.clim-past-discuss.net/cp-2018-9/cp-2018-9-AC3-supplement.pdf

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Interactive comment on Clim. Past Discuss., https://doi.org/10.5194/cp-2018-9, 2018.

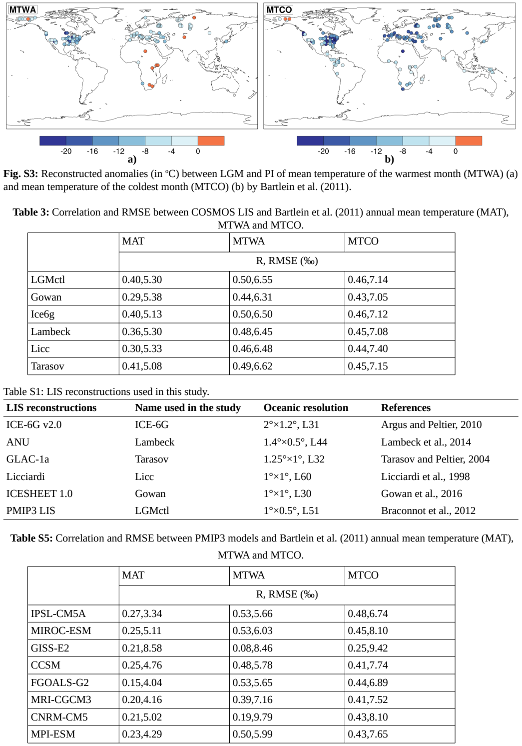

Fig. S3: Reconstructed anomalies (in °C) between LGM and PI of mean temperature of the warmest month (MTWA) (a) and mean temperature of the coldest month (MTCO) (b) by Bartlein et al. (2011).

Table 3: Correlation and RMSE between COSMOS LIS and Bartlein et al. (2011) annual mean temperature (MAT), MTWA and MTCO.

	MAT	MTWA	MTCO
	R, RMSE (‰)		
LGMctl	0.40,5.30	0.50,6.55	0.46,7.14
Gowan	0.29,5.38	0.44,6.31	0.43,7.05
Ice6g	0.40,5.13	0.50,6.50	0.46,7.12
Lambeck	0.36,5.30	0.48,6.45	0.45,7.08
Licc	0.30,5.33	0.46,6.48	0.44,7.40
Tarasov	0.41,5.08	0.49,6.62	0.45,7.15

Table S1: LIS reconstructions used in this study.

LIS reconstructions	**Name used in the study**	**Oceanic resolution**	**References**
ICE-6G v2.0	ICE-6G	2°×1.2°, L31	Argus and Peltier, 2010
ANU	Lambeck	1.4°×0.5°, L44	Lambeck et al., 2014
GLAC-1a	Tarasov	1.25°×1°, L32	Tarasov and Peltier, 2004
Licciardi	Licc	1°×1°, L60	Licciardi et al., 1998
ICESHEET 1.0	Gowan	1°×1°, L30	Gowan et al., 2016
PMIP3 LIS	LGMctl	1°×0.5°, L51	Braconnot et al., 2012

Table S5: Correlation and RMSE between PMIP3 models and Bartlein et al. (2011) annual mean temperature (MAT), MTWA and MTCO.

	MAT	MTWA	MTCO
	R, RMSE (‰)		
IPSL-CM5A	0.27,3.34	0.53,5.66	0.48,6.74
MIROC-ESM	0.25,5.11	0.53,6.03	0.45,8.10
GISS-E2	0.21,8.58	0.08,8.46	0.25,9.42
CCSM	0.25,4.76	0.48,5.78	0.41,7.74
FGOALS-G2	0.15,4.04	0.53,5.65	0.44,6.89
MRI-CGCM3	0.20,4.16	0.39,7.16	0.41,7.52
CNRM-CM5	0.21,5.02	0.19,9.79	0.43,8.10
MPI-ESM	0.23,4.29	0.50,5.99	0.43,7.65

Fig. 1.

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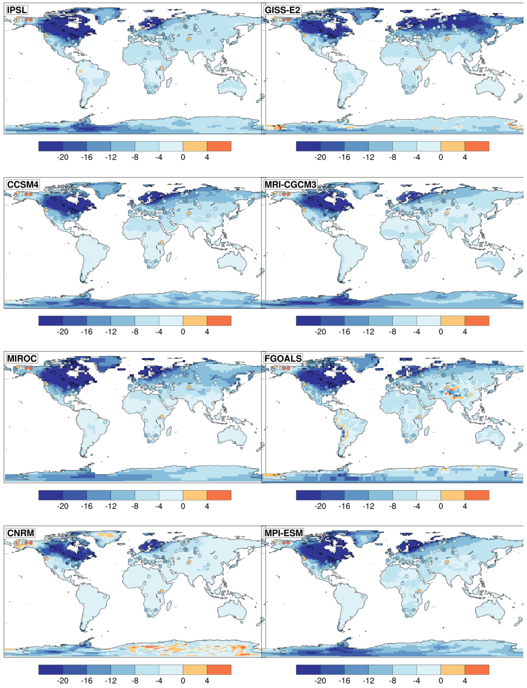

Figure 7: Background color fill: simulated global pattern of annual mean surface temperature over land (T_{2m}) (in °C) changes between the eight PMIP3 model and PI climate. The circles localize the pollen-based reconstructed temperature changes by Bartlein et al. (2011).

Fig. 2.

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