

**Last Interglacial  
model-data mismatch  
partially explained**

P. Bakker and  
H. Renssen

# Last Interglacial model-data mismatch of thermal maximum temperatures partially explained

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## Abstract

The timing of the Last Interglacial (LIG) thermal maximum is highly uncertain. Compilations of maximum LIG temperatures are therefore based on the assumption that maximum warmth occurred synchronously across the globe. Although known to be an oversimplification, the impact of this assumption on temperature estimates has yet to be assessed. We use the LIG temperature evolutions simulated by 9 different climate models to investigate whether the assumption of synchronicity results in a sizeable overestimation of LIG thermal maximum temperatures. We find that for annual temperatures, the overestimation is small, strongly model-dependent (global mean  $0.4 \pm 0.3^\circ\text{C}$ ) and cannot explain the recently published  $0.67^\circ\text{C}$  difference between simulated and reconstructed LIG thermal maximum temperatures. However, if one takes into consideration that temperature proxies are possibly biased towards summer, the overestimation of the LIG thermal maximum based on warmest month temperatures is non-negligible (global mean  $1.1 \pm 0.4^\circ\text{C}$ ) and can at least partly explain the  $0.67^\circ\text{C}$  global model-data difference.

## 1 Introduction

The Last Interglacial period (LIG;  $\sim 130$ – $116$  thousand years before present [ka]) receives increasing attention because of the potential to evaluate climate model performance for a warmer than present-day climate (Otto-Bliesner et al., 2006, 2013; Lunt et al., 2013; Masson-Delmotte et al., 2013) and to constrain the impact of climate feedbacks such as increased melt rates of the major ice sheets in warmer climates (Otto-Bliesner et al., 2006; Bakker et al., 2012, 2013; Stone et al., 2013). To facilitate the model-data comparisons that are crucial in such an evaluation of climate model performance, a number of compilations of reconstructed maximum LIG temperatures have been produced (CAPE Last Interglacial Project Members, 2006; Turney and Jones, 2010; McKay et al., 2011), based on a variety of different temperature proxies,

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retrieved from ice, marine and terrestrial archives. However, because the LIG lies outside the time span covered by  $^{14}\text{C}$ -dating, chronological uncertainties for this period can be up to 5000 yr (Waelbroeck et al., 2008). As a consequence, these compilations of LIG thermal maximum temperatures are based on the assumption that maximum warmth occurred synchronously across the globe. A general conclusion from subsequent evaluations of LIG climate simulations is that models do not capture the degree of LIG warming suggested by proxy-based reconstructions, whether using annual, or warmest month temperatures (Lunt et al., 2013; Otto-Bliesner et al., 2013). For example, Otto-Bliesner et al. (2013) recently performed a comparison between a large number of continental and oceanic records and a LIG (130 ka) time-slice simulation with the CCSM3 model. They find that for the proxy sites in the Northern Hemisphere (NH) extratropical regions (30–90° N), the reconstructed 1.71 °C annual mean temperature anomaly (with respect to pre-industrial; based on a combination of the compilations by Turney and Jones, 2010 and McKay et al., 2011) is considerably underestimated by the CCSM3 model (0.76 °C). This raises the question what causes this model-data mismatch of LIG thermal maximum temperatures.

One partial reason for the mismatch could be that the synchronicity assumption underlying the compilations of the LIG thermal maximum is a non-negligible oversimplification. Several transient modelling experiments for both the Present Interglacial (PIG) and the LIG have shown that there can be large regional differences in the timing of interglacial maximum warmth, in the order of several thousands of years (Renssen et al., 2009, 2012; Bakker et al., 2012). These temporal differences result from latitudinal and seasonal differences in the evolution of the orbital forcing, from the thermal inertia of the oceans and from a variety of climate feedbacks in the climate system, such as the presence of remnant ice sheets from the preceding deglaciation, changes in sea-ice cover, vegetation, meridional overturning strength and monsoon dynamics. Moreover, these complexities in the orbital forcing and its interaction with climate feedbacks, can cause seasonal differences in the timing of interglacial maximum warmth; e.g. the annual mean, summer or winter temperature maxima did possibly not occur

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synchronously. As a consequence, a compilation of reconstructed LIG temperatures that combines LIG maximum temperatures from different regions, seasons and climatic archives, possibly yields temperature anomalies that are larger than the maximum temperatures that occurred at any given time during the LIG period.

We use the results of transient LIG climate simulations performed by 9 different climate models to (i) assess the magnitude and robustness of the possible overestimation of LIG thermal maximum temperatures caused by the assumption of synchronicity in space and time; and (ii) investigate the importance of the geographical region and the season over which the average is made. These results enable us to discuss the degree to which the overestimation of LIG thermal maximum temperatures resulting from the synchronicity assumption can explain the differences found in model-data comparison studies for LIG thermal maximum temperatures.

## 2 Method

LIG temperature time-series from a total of 9 different climate models, ranging from earth system models of intermediate complexity (EMIC) to general circulation models (GCM), have previously been compared in Bakker et al. (2013, 2014). A thorough description of the simulations and climate models can be found there, while an overview is given in Table 1. To investigate the possible overestimation of LIG thermal maximum temperatures, we calculate the temperature anomalies in two different ways: (i) we calculate the largest regionally averaged temperature anomaly for a single 50 yr period (warmest-single-period); (ii) we assume synchronicity of the LIG thermal maximum in space and time by calculating for each individual model grid cell the largest LIG temperature anomaly and combine these single-grid-cell maxima into a regional average (compilation-warmest-periods). In other words, the result of the warmest-single-period method can be regarded as a real estimate of LIG thermal maximum temperatures, while the result from the compilation-warmest-periods is an analogue to the method

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used in proxy-based temperature compilations and yields an overestimated LIG thermal maximum temperature anomaly that did not occur during any LIG 50 yr interval.

In broad agreement with the methods applied in the proxy-based compilations (CAPE Last Interglacial Project Members, 2006; Turney and Jones, 2010; McKay et al., 2011), we limit the timeframe of the two methods to 130–120 ka. Note that for the KCM and MPI-UW simulations, respectively 126–120 and 128–120 ka is used because they do not cover the full period. Sensitivity experiments are performed for 130–125 ka to assess the importance of the definition of this timeframe. To investigate the importance of the spatial domain for which the temperature anomalies are calculated, we look at the global scale, the Northern Hemisphere extratropics (30–90° N), the tropics (30°S–30° N) and the Southern Hemisphere (SH) extratropics (90–30° S). An ongoing debate is whether proxy-based temperatures represent annual mean temperatures or if they include a seasonal bias that could in turn be dependent on the type of proxy and the region under consideration (Schneider et al., 2010; Leduc et al., 2010; Lohmann et al., 2013). To assess the impact on the results of a potential seasonal bias we investigate anomalies of both annual mean temperatures and warmest month temperatures. All calculations are performed for the multi-model-mean (MMM) as well as for the individual models in order to evaluate the robustness of the results. All model output in this study has been regridded to a common 1° × 1° resolution and the temperatures used are atmospheric 2-m-temperature anomalies with respect to pre-industrial values. All time-series are 50 yr averages in order to filter out decadal and sub-decadal variability. Determining the temporal resolution of a proxy-based LIG temperature compilation is ambiguous. Therefore we test the importance of the temporal resolution by performing a sensitivity experiment with 250 yr averaged temperatures instead of 50 yr averages.

### 3 Results

The calculations of the LIG thermal maximum based on the warmest-single-period and the compilation-warmest-period methods, reveal large differences: between the

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individual models, between different geographical regions and between the annual mean and warmest month temperature anomalies. On a global scale the differences in the estimated LIG thermal maximum temperature anomaly between the two different methods are  $0.4^{\circ}\text{C}$  for MMM annual temperatures, with an inter-model spread of  $0.3^{\circ}\text{C}$  ( $1\sigma$ ; Fig. 1 and Table 2). For smaller geographical regions like the NH extratropics, the tropics and SH extratropics the MMM differences in annual LIG thermal maximum temperatures are smaller while the inter-model spread becomes larger in comparison with the mean value ( $0.5 \pm 0.4^{\circ}\text{C}$ ,  $0.2 \pm 0.2^{\circ}\text{C}$  and  $0.3 \pm 0.3^{\circ}\text{C}$  respectively).

For warmest month temperature anomalies we find that the differences between the two methods used to calculate MMM LIG thermal maximum temperature anomalies are much larger and the inter-model spread smaller compared to the calculations based on annual temperatures. For warmest month temperatures the difference between the warmest-single-period and compilation-warmest-period methods is globally  $1.1 \pm 0.4^{\circ}\text{C}$  and regionally  $0.8 \pm 0.5^{\circ}\text{C}$  (NH extratropics),  $0.8 \pm 0.2^{\circ}\text{C}$  (tropics) and  $0.6 \pm 0.3^{\circ}\text{C}$  (SH extratropics; Fig. 2 and Table 2).

The quantification of the potential overestimation of LIG maximum warmth reveals the importance of the spatial domain over which the calculations are performed. The relatively large differences found for the globally averaged LIG thermal maximum based on warmest month temperatures are a direct consequence of the large contrast in the evolution of orbitally-forced summer insolation between the high latitudes of both the NH and the SH (Bakker et al., 2013). The annual global warmest-single-period is characterized by a MMM warming of  $\sim 1^{\circ}\text{C}$  over the mid-to-high latitudes of the NH compared to simulated pre-industrial values, a  $\sim 0.5^{\circ}\text{C}$  warming over the SH mid latitude continents and over Antarctica (Fig. 3). In contrast, the African and Indian monsoon regions show a  $\sim 1^{\circ}\text{C}$  cooling compared to pre-industrial. If this is compared to the annual compilation-warmest-period we do not find a cooling in the monsoon regions and the warming in the mid-to-high latitudes of both hemispheres is on average  $\sim 0.5^{\circ}\text{C}$  larger than the single-warmest-period temperature anomalies. Over the tropical oceans the differences between both methods are small. For warmest month temperatures we find

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a different picture. Because of the contrasting LIG evolution of summer insolation for the NH and the SH, the warmest month global warmest-single-period is characterized by a warming of  $\sim 5^\circ\text{C}$  over the NH continents and  $\sim 2^\circ\text{C}$  over the NH oceans while for the same period simulated SH warmest month temperatures are  $\sim .5^\circ\text{C}$  below pre-industrial values. In contrast, the compilation-warmest-period temperatures in the SH show a  $\sim 0.5^\circ\text{C}$  warming for warmest month temperatures, especially over the continents. NH warming in the compilation-warmest-period is also larger than the global warmest-single-period.

Some aspects of the investigation into the importance of the synchronicity assumption appear strongly model dependent. This is especially so for the calculated overestimation of LIG maximum warmth for the NH extratropics, both for annual and warmest month temperatures (Figs. 1 and 2). This is likely related to important feedbacks that are largely restricted to this region, like the strength of the meridional overturning, Arctic sea-ice evolution and the remnants of NH continental ice sheets from the preceding deglaciation. Note that the latter feedback is only included in the Bern3D simulation. Another inter-model difference that is found especially for annual mean temperatures, is the contrast between high and low resolution models (Fig. 1). The calculated overestimation of LIG maximum warmth is strikingly smaller in Bern3D, CLIMBER2, FAMOUS and LOVECLIM, the lowest resolution models in the model inter-comparison. This difference can be related to two potential causes. Firstly, models with reduced resolution and complexity are known to have a generally more gradual climate evolution in both space and time (Gregory et al., 2005; Bakker et al., 2013) because of the smaller internal variability of these models compared to GCMs. A second possible explanation relates to the fact that the included EMICs all reveal large changes in the meridional overturning circulation (Bakker et al., 2013); changes that arise as internal climate variability of these models, with the exception of the Bern3D simulation that includes prescribed melt water fluxes from remnants of NH continental ice sheets from the preceding deglaciation. Abrupt changes in the meridional overturning circulation act to strongly synchronise simulated LIG maximum temperatures over extensive parts

of the globe and thus decrease the difference between the warmest-single-period and compilation-warmest-periods temperatures.

To assess the possible overestimation of LIG thermal maximum temperatures, two arbitrary choices have to be made. First, we selected the 130–120 ka period to represent the LIG in this analysis, and second, we applied a 50 yr average to the simulated temperature time-series. To test the robustness of the results with respect to these two choices we performed two additional sets of calculations in which we (1) used a 130–125 ka period instead of 130–120 ka and (2) used 250 yr averaged temperature time-series instead of 50 yr averages. Not unexpectedly, we find that the resulting MMM overestimation of LIG thermal maximum temperatures becomes smaller if the LIG period is decreased to 130–125 ka (annual mean global difference of  $0.3 \pm 0.2^\circ\text{C}$  instead of  $0.4 \pm 0.3^\circ\text{C}$ ) or the time averaging increased to 250 yr (annual mean global difference of  $0.3 \pm 0.2^\circ\text{C}$  instead of  $0.4 \pm 0.3^\circ\text{C}$ ; Table 3). However, the main features described above appear robust.

## 4 Discussion

We have shown that in climate models the synchronicity assumption potentially results in a sizeable overestimation of LIG thermal maximum temperatures. In order to see if it can explain part of the reported model-data mismatch (Lunt et al., 2013; Otto-Bliesner et al., 2006, 2013), we compare our results with the findings of Otto-Bliesner et al. (2013). They performed a number of sensitivity experiments with the CCSM3 climate model, with for instance different orbital parameters, and compared their results with proxy-based compilations of Turney and Jones (2010) and McKay et al. (2011). Otto-Bliesner et al. (2013) show that the smallest LIG thermal maximum model-data differences are found in a model run forced with 130 ka forcings and when the comparison is performed solely for the locations from which the proxy-records are derived (for thorough model and scenario description see Otto-Bliesner et al., 2013). Nonetheless, a global mean model-data temperature differences of  $0.67^\circ\text{C}$  is found (0.98 and

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0.31 °C in the reconstructions and simulations respectively). The possible overestimation of the proxy-based temperature estimated as quantified in this study based on the MMM ( $0.4 \pm 0.3$  °C), can only provide a partial explanation of this model-data difference (Fig. 4). We do note that for a number of individual models an annual mean global overestimation of over 0.6 °C is found. It has been proposed that temperature-reconstructions based on for instance ice-core  $\delta^{18}\text{O}$ , alkenones and Mg/Ca, are biased towards a specific season and that this bias depends on the geographical location of the proxy-record (Schneider et al., 2010; Leduc et al., 2010; Lohmann et al., 2013). If the 0.98 °C global temperature increase during the LIG thermal maximum (Otto-Bliesner et al., 2013) would be biased towards the warmest month, the calculated global  $1.1 \pm 0.4$  °C overestimation resulting from the synchronicity assumption could potentially fully explain the model-data difference of 0.67 °C (Fig. 3). Also for specific geographical regions like the tropics, we find that the model-data difference can potentially be explained by the calculated overestimation for the warmest month temperatures (simulated  $0.8 \pm 0.2$  °C with respect to a 0.50 °C model-data difference). In the NH extratropics the results are inconclusive, as individual models show differences over 1 °C but the simulated MMM of  $0.8 \pm 0.5$  °C is small with respect to the 0.67 °C model-data difference. For the SH extratropical regions the calculated MMM overestimation of  $0.6 \pm 0.3$  °C is small compared to the reported model-data difference of 1.40 °C and not even a single model simulation yields a value of over 1 °C. Interestingly, we find that the calculated overestimation of LIG maximum warmth in the CCSM3 model, the model used by Otto-Bliesner et al. (2013) for the model-data comparison, is always larger than the MMM. However, a comparison between the CCSM3 LIG equilibrium simulations presented by Otto-Bliesner et al. (2013) and the transient simulation presented here is far from straightforward and not easily interpreted.

We acknowledge that the presented assessment of the overestimation of LIG maximum warmth is imperfect. The lack of a statistical analyses of the significance of the calculated overestimation compared to the literature-based model-data mismatch is a profound limitation to the current study. However, reliable uncertainty estimates for

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the reconstructed LIG temperature compilations are not available. Furthermore, there are a number of limitations to the climate model simulations. The models included in this study are all known to have specific biases for the present-day climate. Moreover, the included climate models have difficulty to mimic the reconstructed synchronicity between NH and SH high latitude warming during the early LIG (Bakker et al., 2013). Furthermore, the LIG simulations are not all forced with identical climate forcings. Most notably, the CCSM3 and KCM simulations lack transient greenhouse gas concentrations, the Bern3D simulation includes remnants of glacial ice sheets and related melt water fluxes, the CLIMBER2 and MPI-UW simulations include dynamic calculations of vegetation feedbacks while the other models do not and finally the CCSM3, COSMOS, CSIRO and KCM include an accelerated orbital forcing with a potential impact on the simulated internal variability of the climate. The lack of remnant ice sheets in the simulations during the early LIG (except the Bern3D simulation) can potentially impacts the heterogeneity of the thermal maximum (Renssen et al., 2009). Even though Kopp et al. (2009) have shown that already by 129 ka sea level was close to its present-day value, the different phasing for the PIG and the LIG between the NH continental ice sheet regression and NH peak summer insolation could potentially impact the validity of the maximum warmth heterogeneity assumption. The final and possibly most important point of critique, is the fact that it is obviously not ideal to use the tools that require evaluation, to evaluate the reference dataset. Notwithstanding, until chronologies for the LIG become better constrained, climate models are the only tool with which an assessment of the possible overestimation of LIG thermal maximum temperatures can be made. We argue that the outcomes presented in this study are helpful in understanding the large differences between reconstructed and simulated LIG temperatures.

## 5 Conclusions

With transient simulations covering the LIG period by 9 different climate models we investigate whether the assumption of synchronicity in space and time of the LIG thermal maximum that underlies compilations of reconstructed LIG temperatures, results in a sizable overestimation of this thermal maximum. For annual mean temperatures, the calculated overestimation is small, strongly model-dependent (global MMM of  $0.4^{\circ}\text{C}$  with a  $\pm 0.3^{\circ}\text{C}$  inter-model spread) and cannot explain the  $0.67^{\circ}\text{C}$  model-data difference described by Otto-Bliesner et al. (2013). However, if reconstructed LIG temperatures would prove to be partially biased towards the warm season, the calculated global and tropical overestimation of the LIG thermal maximum based on simulated warmest month temperatures (global MMM  $1.1 \pm 0.4^{\circ}\text{C}$ ; tropics MMM  $0.8 \pm 0.2^{\circ}\text{C}$ ) can potentially fully explain the global and tropical model-data differences described by Otto-Bliesner et al. (2013),  $0.67$  and  $0.33^{\circ}\text{C}$ , respectively. For the extratropics, the overestimation can explain only part of the model-data differences, indicating that additional explanations are required. Notwithstanding that the exact magnitude of the calculated overestimation is depending on applied methodology and climate models, our findings suggest that the overestimation provides a non-negligible partial explanation of the LIG thermal maximum model-data mismatch.

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- Gregory, J. M., Dixon, K. W., Stouffer, R. J., Weaver, A. J., Driesschaert, E., Eby, M., Fichfet, T., Hasumi, H., Hu, A., Jungclaus, J. H., Kamenkovich, I. V., Levermann, A., Montoya, M., Murakami, S., Nawrath, S., Oka, A., Sokolov, A. P., and Thorpe, R. B.: A model intercomparison of changes in the Atlantic thermohaline circulation in response to increasing atmospheric CO<sub>2</sub> concentration, *Geophys. Res. Lett.*, 32, L12703, doi:10.1029/2005GL023209, 2005. 745
- Gröger, M., Maier-Reimer, E., Mikolajewicz, U., Schurgers, G., Vizcaíno, M., and Winguth, A.: Vegetation-climate feedbacks in transient simulations over the last interglacial (128,000–113,000 yr BP), in: *The Climatic of the Past Interglacials*, edited by: Sirocko, F., Elsevier, New York, 563–572, 2007. 754
- Jones, P. D., Gregory, J., Thorpe, R., Cox, P., Murphy, J., Sexton, D., and Valdes, P.: Systematic Optimisation and climate simulations of FAMOUS, a fast version of HadCM3, *Clim. Dynam.*, 25, 189–204, 2005. 754
- Kopp, R. E., Simons, F. J., Mitrovica, J. X., Maloof, A. C., and Oppenheimer, M.: Probabilistic assessment of sea level during the last interglacial stage, *Nature*, 462, 863–867, 2009. 748
- Leduc, G., Schneider, R., Kim, J. H., and Lohmann, G.: Holocene and Eemian sea surface temperature trends as revealed by alkenone and Mg/Ca paleothermometry, *Quaternary Sci. Rev.*, 29, 989–1004, 2010. 743, 747
- Lohmann, G., Pfeiffer, M., Laepple, T., Leduc, G., and Kim, J.-H.: A model–data comparison of the Holocene global sea surface temperature evolution, *Clim. Past*, 9, 1807–1839, doi:10.5194/cp-9-1807-2013, 2013. 743, 747
- Lunt, D. J., Abe-Ouchi, A., Bakker, P., Berger, A., Braconnot, P., Charbit, S., Fischer, N., Herold, N., Jungclaus, J. H., Khon, V. C., Krebs-Kanzow, U., Langebroek, P. M., Lohmann, G., Nisancioglu, K. H., Otto-Bliesner, B. L., Park, W., Pfeiffer, M., Phipps, S. J., Prange, M., Rachmayani, R., Renssen, H., Rosenbloom, N., Schneider, B., Stone, E. J., Takahashi, K., Wei, W., Yin, Q., and Zhang, Z. S.: A multi-model assessment of last interglacial temperatures, *Clim. Past*, 9, 699–717, doi:10.5194/cp-9-699-2013, 2013. 740, 741, 746
- Marsland, S. J., Haak, H., Jungclaus, J. H., Latif, M., and Röske, F.: The Max-Planck-Institute global ocean/sea ice model with orthogonal curvilinear coordinates, *Ocean Model.*, 5, 91–127, 2003. 754
- Masson-Delmotte, V., Schulz, M., Abe-Ouchi, A., Beer, J., Ganopolski, A., González Rouco, J. F., 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

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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. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M., Cambridge University Press, Cambridge, UK and New York, NY, USA, 2013. 740

5 McKay, N. P., Overpeck, J. T., and Otto-Bliesner, B. L.: The role of ocean thermal expansion in Last Interglacial sea level rise, *Geophys. Res. Lett.*, 38, L14605, doi:10.1029/2011GL048280, 2011. 740, 741, 743, 746

10 Muller, S. A., Joos, F., Edwards, N. R., and Stocker, T. F.: Water mass distribution and ventilation time scales in a cost-efficient, three-dimensional ocean model, *J. Climate*, 19, 5479–5499, 2006. 754

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, 2006. 740, 746

15 Otto-Bliesner, B. L., Rosenbloom, N., Stone, E. J., McKay, N. P., Lunt, D. J., Brady, E. C., and Overpeck, J. T.: How warm was the last interglacial?, *New model – data comparisons*, *Philos. T. Roy. Soc. A*, 371, 1–20, 2013. 740, 741, 746, 747, 749, 760

20 Park, W., Keenlyside, N., Latif, M., Stroh, A., Redler, R., Roeckner, E., and Madec, G.: Tropical Pacific climate and its response to global warming in the Kiel Climate Model, *J. Climate*, 22, 71–92, 2009. 754

Petoukhov, V., Ganopolski, A., Brovkin, V., Claussen, M., Eliseev, A., Kubatzki, C., and Rahmstorf, S.: CLIMBER-2: a climate system model of intermediate complexity, Part I: Model description and performance for present climate, *Clim. Dynam.*, 16, 1–17, 2000. 754

25 Phipps, S. J., Rotstayn, L. D., Gordon, H. B., Roberts, J. L., Hirst, A. C., and Budd, W. F.: The CSIRO Mk3L climate system model version 1.0 – Part 1: Description and evaluation, *Geosci. Model Dev.*, 4, 483–509, doi:10.5194/gmd-4-483-2011, 2011. 754

Phipps, S. J., Rotstayn, L. D., Gordon, H. B., Roberts, J. L., Hirst, A. C., and Budd, W. F.: The CSIRO Mk3L climate system model version 1.0 – Part 2: Response to external forcings, *Geosci. Model Dev.*, 5, 649–682, doi:10.5194/gmd-5-649-2012, 2012. 754

30 Renssen, H., Seppa, H., Heiri, O., Roche, D. M., Goosse, H., and Fichefet, T.: The spatial and temporal complexity of the Holocene thermal maximum, *Nat. Geosci.*, 2, 411–414, 2009. 741, 748

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- Renssen, H., Seppa, H., Crosta, X., Goosse, H., and Roche, D. M.: Global characterization of the Holocene Thermal Maximum, *Quaternary Sci. Rev.*, 48, 7–19, 2012. 741
- Ritz, S. P., Stocker, T. F., and Joos, F.: A coupled dynamical ocean-energy balance atmosphere model for paleoclimate studies, *J. Climate*, 24, 349–375, 2011a. 754
- 5 Ritz, S. P., Stocker, T. F., and Severinghaus, J. P.: Noble gases as proxies of mean ocean temperature: sensitivity studies using a climate model of reduced complexity, *Quaternary Sci. Rev.*, 30, 3728–3741, 2011b. 754
- Roeckner, E., Bäuml, G., Bonaventura, L., Brokopf, R., Esch, M., Giorgetta, M., Hagemann, S., Kirchner, I., Kornblueh, L., Manzini, E., Rhodin, A., Schlese, U., Schulzweida, U., and Tompkins, A.: The Atmospheric General Circulation Model ECHAM5, Part I: Model Description, Technical report, MPI-Report 349, Max Planck Institute for Meteorology, Hamburg, Germany, 2003. 754
- 10 Schneider, B., Leduc, G., and Park, W.: Disentangling seasonal signals in Holocene climate trends by satellite-model-proxy integration, *Paleoceanography*, 25, PA4217, doi:10.1029/2009PA001893, 2010. 743, 747
- Schurgers, G., Mikolajewicz, U., Gröger, M., Maier-Reimer, E., Vizcaíno, M., and Winguth, A.: The effect of land surface changes on Eemian climate, *Clim. Dynam.*, 29, 357–373, 2007. 754
- Smith, R. S.: The FAMOUS climate model (versions XFXWB and XFHCC): description update to version XDBUA, *Geosci. Model Dev.*, 5, 269–276, doi:10.5194/gmd-5-269-2012, 2012. 754
- 20 Smith, R. S. and Gregory, J.: The last glacial cycle: transient simulations with an AOGCM, *Clim. Dynam.*, 38, 1545–1559, 2012. 754
- Stone, E. J., Lunt, D. J., Annan, J. D., and Hargreaves, J. C.: Quantification of the Greenland ice sheet contribution to Last Interglacial sea level rise, *Clim. Past*, 9, 621–639, doi:10.5194/cp-9-621-2013, 2013. 740
- 25 Turney, C. S. M. and Jones, R. T.: Does the Agulhas Current amplify global temperatures during super-interglacials?, *J. Quaternary Sci.*, 25, 839–843, 2010. 740, 741, 743, 746
- Waelbroeck, C., Frank, N., Jouzel, J., Parrenin, F., Masson-Delmotte, V., and Genty, D.: Transferring radiometric dating of the last interglacial sea level high stand to marine and ice core records, *Earth Planet. Sc. Lett.*, 265, 183–194, 2008. 741
- 30



**Table 1.** Overview of transient LIG climate simulations. For each simulation included in this study the model name is given, the period for which the simulation is performed (in thousands of years before present), the included forcings (Orb = orbital; acc = 10-fold acceleration of orbital forcing; GHG = Greenhouse gas concentrations; Ice = remnants of glacial continental ice sheets in NH; FWF = freshwater fluxes related to remnant ice sheets), components that are included in addition to the atmosphere, ocean and sea-ice, the model complexity (EMIC = earth system model of intermediate complexity; GCM = general circulation model) and references to publications in which more details on the LIG simulations and the model specifics can be found.

Model name	Period	Included forcings	Additional components	Model complexity	Reference
Bern3D	130–115	Orb, GHG, Ice, FWF		EMIC	Edwards and Marsh (2005) Muller et al. (2006) Ritz et al. (2011a, b) Bakker et al. (2013)
CCSM3	130–115	Orb (acc)		GCM	Collins et al. (2006) Bakker et al. (2013)
CLIMBER2	130–115	Orb, GHG	Vegetation	EMIC	Petoukhov et al. (2000) Bakker et al. (2013)
COSMOS	130–115	Orb (acc), GHG		GCM	Roeckner et al. (2003) Marsland et al. (2003)
CSIRO	130–115	Orb (acc) GHG		GCM	Phipps et al. (2011, 2012)
FAMOUS	130–115	Orb, GHG		GCM	Gordon et al. (2000) Jones et al. (2005) Smith and Gregory (2012) Smith (2012) Bakker et al. (2013)
KCM	126–115	Orb (acc)		GCM	Park et al. (2009) Bakker et al. (2013)
LOVECLIM	130–115	Orb, GHG		EMIC	Goosse et al. (2010) Bakker et al. (2013) Bakker et al. (2013)
MPI-UW	128–115	Orb, Prognostic $p\text{CO}_2$	Vegetation, Marine carbon cycle, biogeochemistry	GCM	Schurgers et al. (2007) Gröger et al. (2007) Bakker et al. (2013)

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**Table 2.** MMM overestimation of LIG maximum warmth. Simulated MMM LIG temperature anomalies ( $^{\circ}\text{C}$ ) for the single-warmest-period and for compilation-warmest-periods. Values are given for annual mean temperatures and for temperatures of the warmest month as well as for 4 different geographical regions: global, NH extratropical ( $30\text{--}90^{\circ}\text{N}$ ), Tropics ( $30^{\circ}\text{S--}30^{\circ}\text{N}$ ) and SH extratropical ( $90\text{--}30^{\circ}\text{S}$ ). The last column gives the difference between the two methods and the inter-model spread ( $1\sigma$ ). All values are anomalies compared to simulated present-day temperatures. The warmest-single-period is the largest 50 yr temperature anomaly found in the average regional temperature evolution. On the other hand, the compilation-warmest-periods follows from a regional average over the highest 50 yr temperature anomalies found in each individual grid cell within that region. Calculations are performed for the 130–120 ka period of the LIG.

Geographic Region		Warmest-single-period ( $^{\circ}\text{C}$ )	Compilation-warmest-period ( $^{\circ}\text{C}$ )	Difference $\pm 1\sigma$ ( $^{\circ}\text{C}$ )
Global	Annual	0.4	0.8	$0.4 \pm 0.3$
	Warmest month	1.3	2.4	$1.1 \pm 0.4$
NH extratropics	Annual	0.9	1.5	$0.5 \pm 0.4$
	Warmest month	3.8	4.6	$0.8 \pm 0.5$
Tropics	Annual	0.3	0.5	$0.2 \pm 0.1$
	Warmest month	1.2	2.0	$0.8 \pm 0.2$
SH extratropics	Annual	0.5	0.9	$0.3 \pm 0.3$
	Warmest month	0.4	1.0	$0.6 \pm 0.3$

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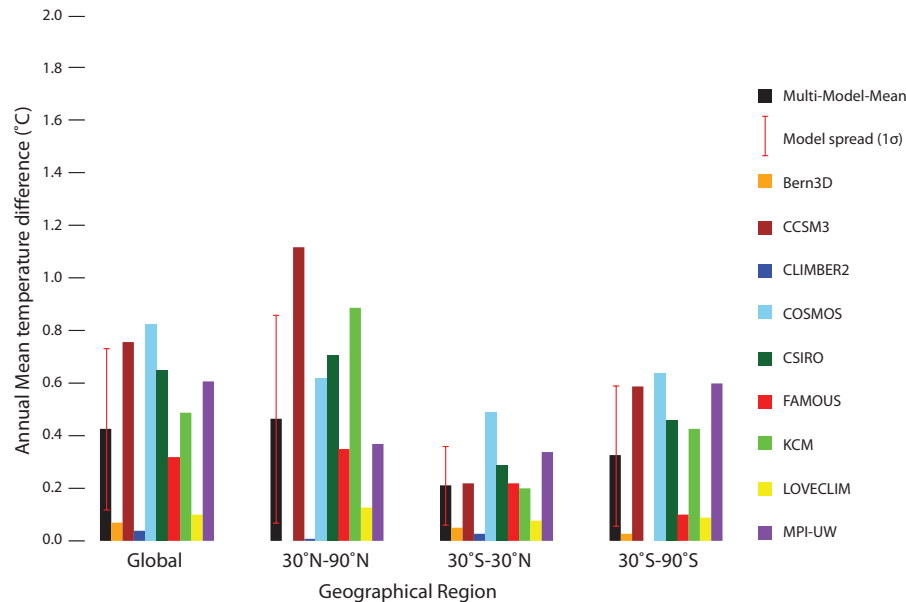
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**Table 3.** Robustness of MMM overestimation of LIG maximum warmth. Calculated MMM overestimation of LIG maximum warmth (mean  $\pm 1\sigma$ ; °C) and the dependence of the results on the two main choices: timeframe of the LIG period over which the calculations are performed (130–120 ka in columns 3 and 4; 130–125 ka in column 5) and the temporal resolution of the simulated temperature time-series (50 yr averages in columns 3 and 5; 250 yr averages in column 4). Values are given for annual mean temperatures and for temperatures of the warmest month as well as for 4 different geographical regions: global, NH extratropical (30–90° N), Tropics (30° S–30° N) and SH extratropical (90–30° S).

Geographic Region		130–120 ka & 50 yr averages	130–120 ka & 250 yr averages	130–125 ka & 50 yr averages
Global	Annual	0.4 $\pm$ 0.3	0.2 $\pm$ 0.2	0.3 $\pm$ 0.2
	Warmest month	1.1 $\pm$ 0.4	0.7 $\pm$ 0.2	0.7 $\pm$ 0.3
NH extratropics	Annual	0.5 $\pm$ 0.4	0.2 $\pm$ 0.2	0.3 $\pm$ 0.3
	Warmest month	0.8 $\pm$ 0.5	0.3 $\pm$ 0.2	0.7 $\pm$ 0.5
Tropics	Annual	0.2 $\pm$ 0.1	0.1 $\pm$ 0.1	0.1 $\pm$ 0.1
	Warmest month	0.8 $\pm$ 0.2	0.5 $\pm$ 0.1	0.5 $\pm$ 0.3
SH extratropics	Annual	0.3 $\pm$ 0.3	0.2 $\pm$ 0.2	0.3 $\pm$ 0.3
	Warmest month	0.6 $\pm$ 0.3	0.3 $\pm$ 0.2	0.5 $\pm$ 0.3



**Fig. 1.** Overestimation of LIG maximum warmth based on annual mean temperatures. Differences between the compilation-warmest-periods and the warmest-single-period methods to calculate the simulated LIG thermal maximum annual mean temperature anomalies ( $^{\circ}\text{C}$ ). Results are given for 4 different geographical regions and for MMM temperature differences (black with  $1\sigma$  inter-model spread in red) and for the 9 individual model runs.

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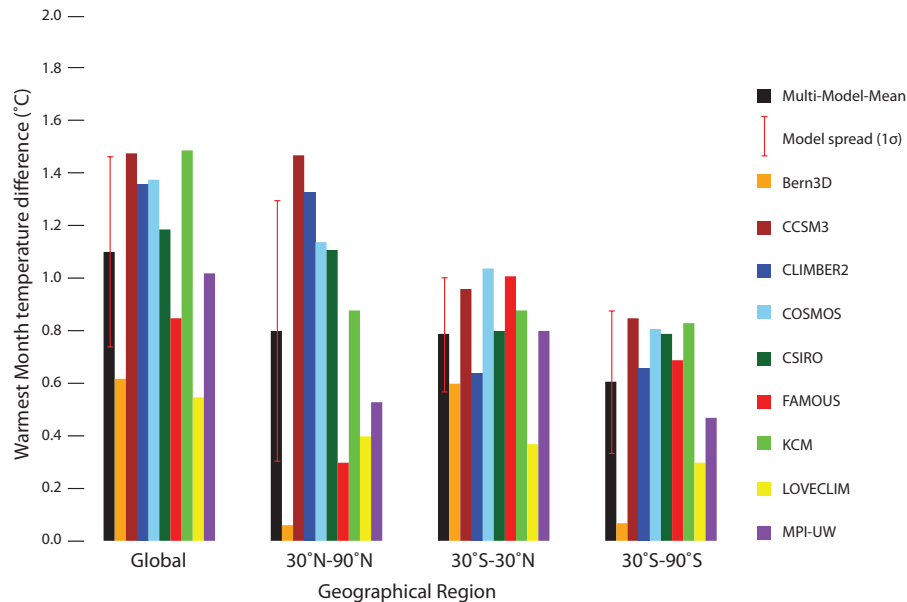
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**Fig. 2.** Overestimation of LIG maximum warmth based on warmest month temperatures. Differences between the compilation-warmest-periods and the warmest-single-period methods to calculate the simulated LIG thermal maximum warmest month temperature anomalies ( $^{\circ}\text{C}$ ). Results are given for 4 different geographical regions and for MMM temperature differences (black with  $1\sigma$  inter-model spread in red) and for the 9 individual model runs.

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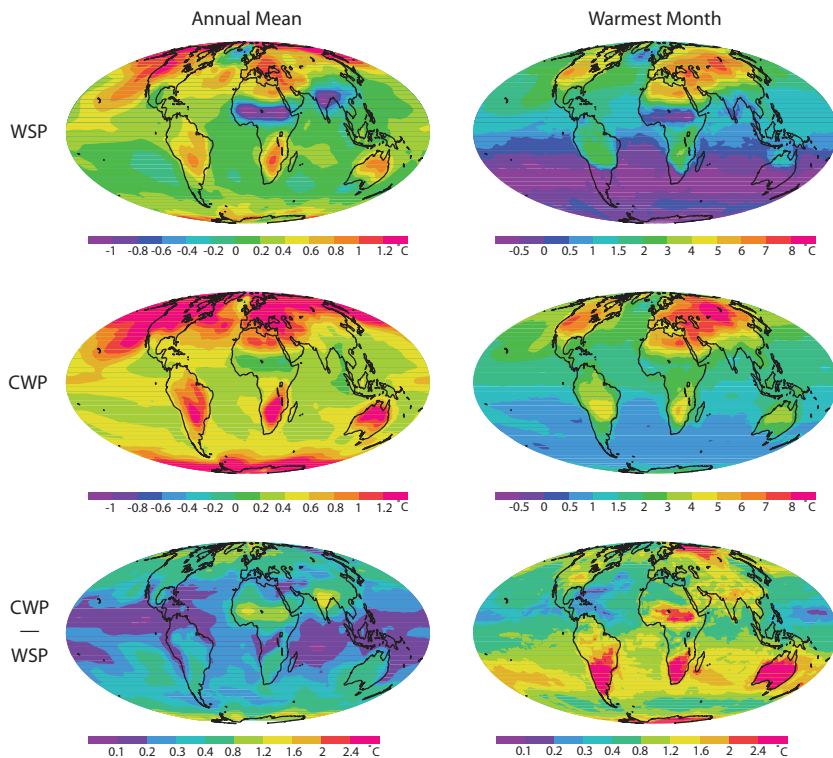
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**Fig. 3.** Spatial differences in quantified overestimation of LIG maximum temperatures. Map of MMM LIG maximum temperature anomalies ( $^{\circ}\text{C}$ ) compared to pre-industrial for the warmest-single-period (WSP, top row panels), the compilation-warmest-period (CWP, middle row panels) and the difference between the two methods (CWP-WSP, bottom row panels). Maps are presented for both simulated annual mean and warmest month temperatures. Warmest-single-period results shown here are based on the globally averaged single warmest period. Note the differences and the non-linearity in the colour scales.

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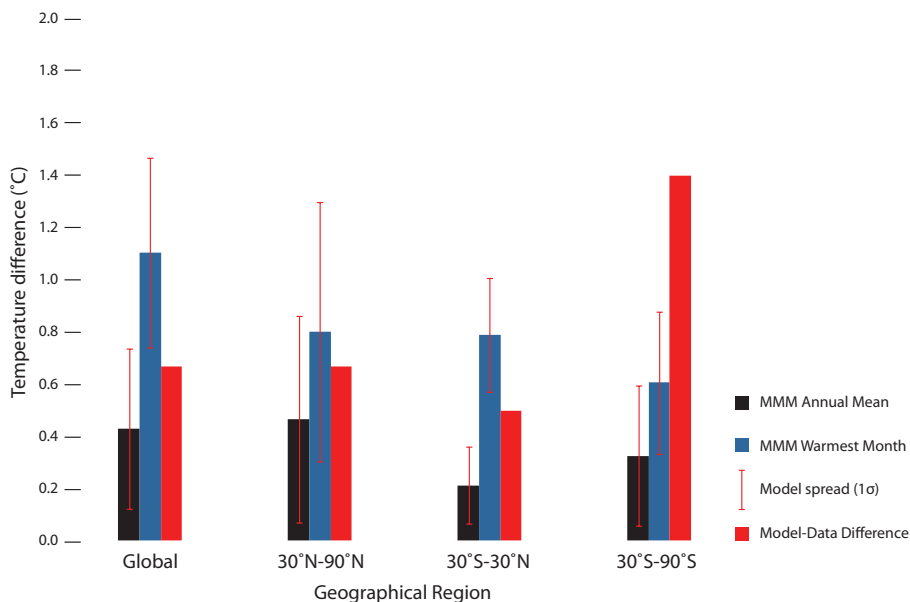
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**Fig. 4.** Comparison between calculated overestimation of LIG thermal maximum temperatures and reported LIG model-data mismatch. The calculated MMM overestimation of annual mean (black) and warmest month (blue) LIG thermal maximum temperatures (°C) including inter-model spread ( $1\sigma$ ; red) compared with the model-data mismatch (red) reported by Otto-Bliesner et al. (2013). Values are given for 4 different geographical regions. The model-data mismatch is based on a combination of terrestrial and oceanic data, comparison at proxy locations only and on a CCSM3 simulation forced with 130 ka forcings (see for details Otto-Bliesner et al., 2013).

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