Reply to Anonymous Referee #1

Comment:

This study presents an extensive set of climate model simulations focusing on the Last Interglacial (LIG) climate and in particular on the impact of changes in the characteristics of the Greenland Ice Sheet (GIS) on simulated surface temperatures and how these results compare to proxy-based LIG temperatures. However, the sheer number of experiments, some of which do not have a clear function as far as I can tell, make the manuscript overall difficult to follow and makes that it lacks focus. If these issues and a number of comments and questions are answered I see the manuscript fit for publication in Climate of the Past.

Reply

We thank the Anonymous Referee #1 for the valuable and in-depth comments on our manuscript. These comments and suggestions certainly help to increase its quality. We do agree that the manuscript is too long and therefore lacks focus. To this end, we have removed from the study some of the model simulations that do not directly relate to the main topic of the manuscript and thus provide a more concise story. This is clarified later in the reply, and highlighted in the revised version of the manuscript.

Main comment:

The aim of the manuscript seems to be to determine what the impact is of changes in the characteristics of the GIS on surface temperatures and how this impacts the model-data comparison of LIG temperatures. This is a very relevant question and the presented sensitivity experiments with different sizes of the GIS allow one to investigate which size yields the best model-data comparison with respect to surface temperature anomalies. However, while the resulting temperature changes from the sensitivity experiments with different sizes of the GIS are thoroughly discussed (perhaps too extensive, see one of the next points), what lacks is a good discussion of these results and their implications. The manuscript would greatly improve if it would present less detailed descriptions of the results and more interpretation and a deepened discussion. Here I'm thinking about questions like what size of the GIS yields the best model-data comparison? Through which mechanisms do changes in the GIS geometry change surface temperatures in the surrounding regions? How do the results compare to other data sources (ice core data for instance) and model experiments (GCMs and ice sheet models) and, finally, if indeed the results allow one to determine whether or not including GIS changes give an improvement of the model-data comparison, is for the right reason? These issues are certainly partly discussed throughout the manuscript, for instance in lines 26-29 of page 961 and lines 1-14 of page 962, but since they are the main topics of the manuscript (and the most novel aspect of it) I think they should be more thoroughly discussed and appear both in the abstract and the conclusion.

Reply

The question regarding which size of GIS yields the best model-data comparison is answered in the form of three tables added in the Supplementary material and mentioned in the revised version. The three tables contain the RMSD values between the three different datasets used in this study (CAPE Last Interglacial Project Members, 2006; Turney and Jones, 2010; Capron et al., 2014) and the simulations with different GIS configurations calculated at different time slices and for annual mean and local summer. We have decided to add tables rather than fully include it in the manuscript for two reasons. Firstly, due to the large amount of data, creating model-data comparison maps for each simulation would results in a too long manuscript that would again lack focus. Secondly, the purpose of this manuscript is not to determine which GIS size yields the best model-data agreement, but to determine the influence of GIS changes on global climate during the LIG. The reason for choosing only one reduced GIS configuration in the model-data comparison of the original manuscript is that both proxy datasets from CAPE Last Interglacial Project Members (2006) and Turney and Jones (2010) indicate a significant warming in the northern high latitudes, therefore we have considered to take the reduced GIS simulation which indicates the strongest warming in order to increase the model-data agreement. From the tables is also clear that the main conclusion did not change since the proxy-based temperature anomalies by CAPE Last Interglacial Project Members (2006) indicate the best agreement with the simulation with preindustrial GIS (LIG-ctl), while the Turney and Jones (2010) dataset fits best to the simulation with reduced GIS and changes in albedo (LIG-1300m-alb). For the new proxy-based dataset that is included in the revised version of the manuscript (Capron et al., 2014), we find the best model-data agreement for summer at 125 kyr BP in the LIG-1300m-alb simulation. However, this result is not conclusive with respect to the size of GIS because we do not have other GIS configuration simulations for this time slice.

In the revised manuscript, we have reorganized the Results and Discussion sections in a more clear and focused manner. The description of the results has been shortened. We have also included in the revised discussion the possible mechanisms that lead to changes in surrounding temperatures due to changes in GIS. The warming in the northern high latitudes during winter can be explained by a delayed response to a warming occurring in October (Fig. R1) which is caused by positive sea-ice-albedo feedbacks. The mechanism behind the warming in the southern high latitudes is explained as well in the Discussion section and later in the reply.

Whether the model-data improvement is for the right reason we cannot say for sure. Other factors like glacial memory effects on 130 kyr BP are not considered in this study as such effects are not well represented in the models and cannot be fully reproduced.

We have mentioned all these main topics in the conclusions of the revised manuscript.

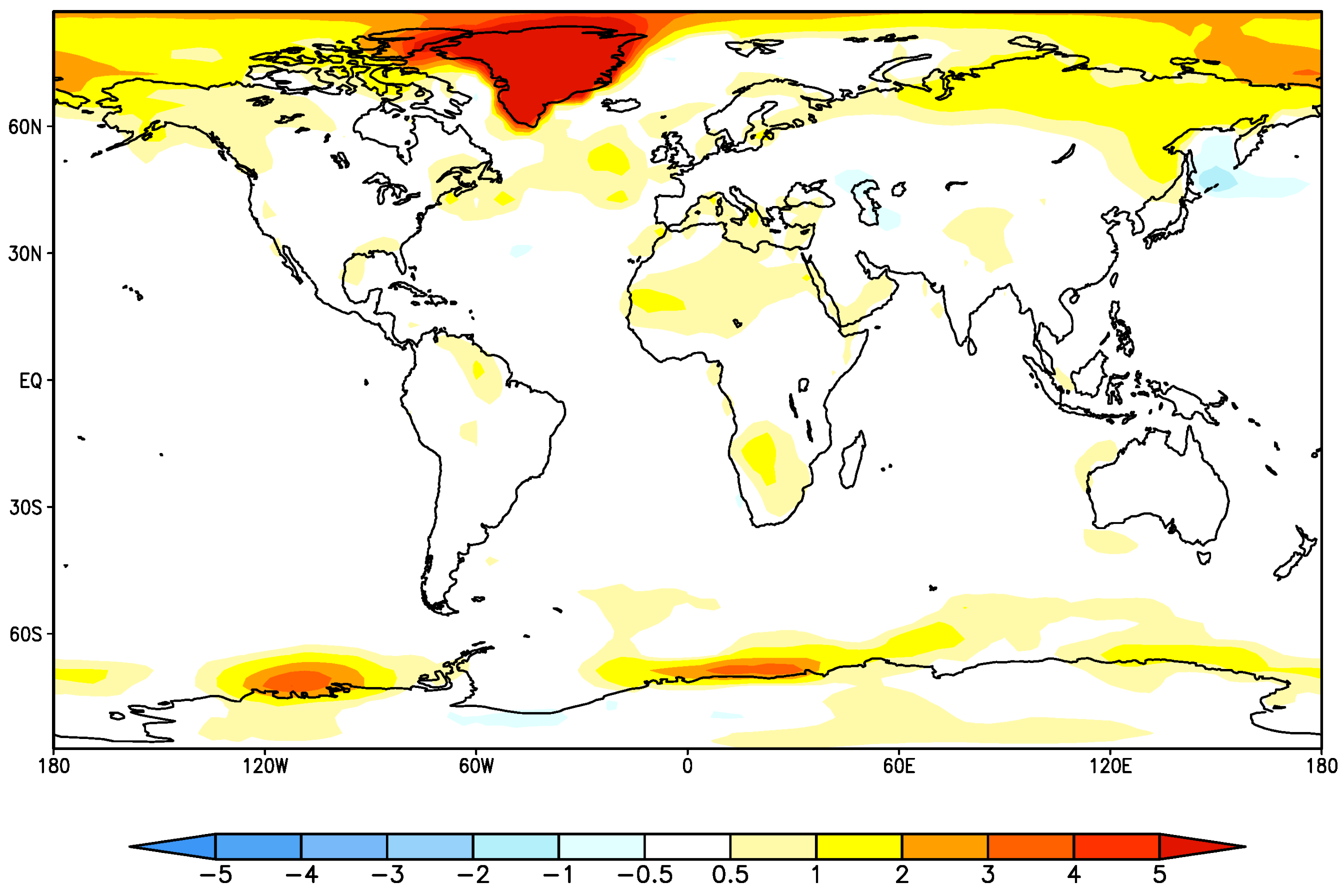

Figure R1. Effect of Greenland Ice Sheet elevation and albedo in the 130 kyr BP simulation. October mean surface temperature (TS) anomalies (in °C) for simulations LIG-1300 m-alb minus LIG-ctl.

General comments:

Comment:

1) The results section is rather long and hard to follow. I see a couple of things that could be changed to improve this. Firstly, since all numbers are given in the table and figures, this part could be more focused on the most important finding. Secondly, the reader could be guided through this section by including a short introduction of what is to come. Finally, this section would improve significantly if it is made clear what the purpose is of the different sensitivity experiments and why they are discussed in a certain order.

Reply

We have shortened the Results section and made it more focused. We also give a short description of what is to follow. The purpose of different sensitivity simulations is clarified in the revised version of the manuscript.

Comment:

2) There are a couple of simulations which do not have a clear purpose as far as I can tell. Can the authors clarify the reason of including the simulations with different CH4 levels (LIG-1300m-alb-CH4) and the experiments LIG-GHG, LIG-125k and GI? And similarly, why do the authors include a HOL-tr simulation? What does it tell about the main topic of this manuscript, being the impact of changes in the characteristics of the GIS on surface temperatures during the LIG?

Reply

The reason for including a simulation with different CH_4 values is indeed not clear in the original manuscript, but an explanation is added in the revised version. The LIG-1300m-alb-CH_4 simulation has been performed in order to have one LIG simulation that has identical GHG concentrations as the PI simulation (Wei et al., 2012) which was run with concentrations as proposed by PMIP2. This simulation is needed in order to be able to quantify the combined as well as separated effects of insolation and changes in GIS and albedo on global climate, without any changes in GHG concentrations since this is not the focus of this study. The effects of different CH_4 values are displayed in Fig. S2 in the Supplementary material of the initial manuscript, but this figure is removed from the revised version since is indeed not of relevant importance to the main story. However, the LIG-1300m-alb-CH_4 simulation is not used in the model-data comparison because all other LIG experiments with reduced GIS do not have identical GHG values like PI simulation from Wei et al. (2012). Therefore, in order to be consistent in the model-data comparison of the proxies with different LIG simulations, we use the simulation LIG-1300m-alb since it has identical GHG concentrations with those used in the other simulations that consider a reduction in GIS, as well as in the LIG-ctl simulation. We therefore keep the LIG-1300m-alb-CH_4 simulation in the revised manuscript in order to be able to quantify the exclusive effects of insolation and changes in GIS configuration on the global climate.

The LIG-GHG simulation was run according to PMIP3 protocol and while this simulation indeed does not contribute to the main topic of the study we decided nevertheless to include it in order to show that the effects of lower GHG concentrations used in the LIG-GHG simulation do not have a large scale influence on the global surface temperature when compared to our LIG control simulation (LIG-ctl). But since it is not part of the main story, we have kept this figure in the Supplementary material (Fig. S1).

The LIG-125k simulation was included in order to see whether changes in insolation would play a major role in the model-data comparison agreement, and also to be able to perform a comparison with results from Otto-Bliesner et al. (2013), who also conduct model simulations for the 125 kyr BP time slice and compare these results to the proxy-based dataset used also in our study. In the revised version of the manuscript, additionally a comparison with the proxy dataset by Capron et al. (2014) is performed for both time slices, namely 130 and 125 kyr BP. We keep the results from the LIG-125k simulation in the Supplementary material since the focus of this study is on the 130 kyr BP time slice.

The GI simulation was included as a “side story” with respect to changes in insolation but for simplifying the story we have removed it in the revised manuscript since it does not add any relevant contribution to the main topic. The HOL-x0.5 simulation is also removed for the same reasons.

The HOL-tr transient simulation indeed does not contribute to the main topic of the paper, namely the influence of GIS on the surface temperature. However, we decided to include it as a temperature evolution reference with respect to the LIG temperature evolution.

Comment:

3) Some of the presented results are not clearly linked to the main topic of this manuscript. What is the link of the main topic with sections 3.2 and 4.3? Making more clear why these results are presented and how they relate to the main research questions of the manuscript would greatly improve the structure, flow and therewith readability of the manuscript.

Reply

We have indeed failed to provide a clear explanation behind the decision to include transient simulations in our study. However, we hope that the revised manuscript presents the reasons more clearly. The reason for including LIG transient simulations in our study is to to be able to calculate the maximum LIG warmth with respect to summer and annual mean, and use these results in the model-data comparison since proxies from the CAPE Last Interglacial Project Members (2006) and Turney and Jones (2010) datasets are considered to indicate summer and annual mean signals, respectively, at the maximum LIG warmth. These results indeed lead to an increase in the model-data agreement. The proxy dataset from CAPE Last Interglacial Project Members (2006) indicates best agreement with local summer (warmest month) at the summer maximum LIG warmth (in the LIG-ctl-tr simulation), while the proxies from Turney and Jones (2010) compilation fit best to annual mean at the annual mean maximum LIG warmth (in the LIG-1300m-alb-tr simulation). This way we are able to tackle one uncertainty in the proxy data interpretation.

We have decided to display in a figure the temperature evolution during the LIG in order to give the viewer a feeling on how these results look, before including them in the model-data comparison. However, for a better flow of the story, we have kept only the figure with temperature evolution in the northern high latitudes (Fig. 5) and moved the figures with middle and low latitude averages in the Supplementary material (now Figs. S2 and S3). We also shortened the parts that cover this topic in the Results and Discussion sections for a better readability.

Comment:

4) A difficulty in this study is the lack of a clear explanation of the mechanisms that cause the high-latitude Southern Hemisphere warming resulting from the lowering of the GIS. Although a fair point is made on lines 23-24 of page 957 that it is beyond the scope of this manuscript, I have problems with the fact that the manuscript does refer to these changes in a number of occasions. For instance line 3 page 937 indicates that this study will go beyond investigating the impact of a reduced GIS on the Northern Hemisphere, thus into the Southern Hemisphere. On lines 14-19 of page 964 the results of the model-data comparison is discussed for the high-latitudes of the Southern Hemisphere and compared to how other models perform. Either do not discuss these regions or do, but then also explain the mechanisms behind it.

Reply

One possible mechanism behind the changes in the Southern Hemisphere caused by a reduction of GIS is related to an increase in the AMOC, which transports more heat from the downwelling areas in the northern high latitudes towards the Southern Hemisphere (Fig. R2). One possible explanation for an enhanced AMOC may be an increase in the salinity in the northern North Atlantic Ocean of up to +1 psu (Fig. R3), increasing thus the density of the water in the downwelling locations. Changes in AMOC due to a reduction of GIS can be additionally explained by an increase in the atmospheric flow displayed in Fig. 11 of the revised manuscript. The low pressure system over Greenland and the high pressure system above Europe become more extreme, enhancing the north-eastward air circulation. However, convection cannot be the only explanation for the southern high latitudes warmth, since the heat would be dispersed towards the Southern Hemisphere. We however note a large scale warming in the subsurface of the Southern Ocean which is probably caused by positive feedbacks. This warming may be related to changes in the water stratification. We observe an invigorated vertical mixing in the northern North Atlantic Ocean (Fig. R4a) and a suppressed vertical mixing in the Southern Ocean (Fig. R4b), the latter causing the heat at subsurface to be preserved. The Southern Ocean has a large heat capacity leading to a long memory of the system. Lags of up the three months occur in the surface layer including sea ice (amplifying factor via positive ice-albedo and ice-insulation feedbacks), while long-term lags occur in deeper levels below the summer mixed layer that store seasonal thermal anomalies (Renssen et al., 2005).

The explanation of these mechanisms are included in the Discussion section of the revised manuscript.

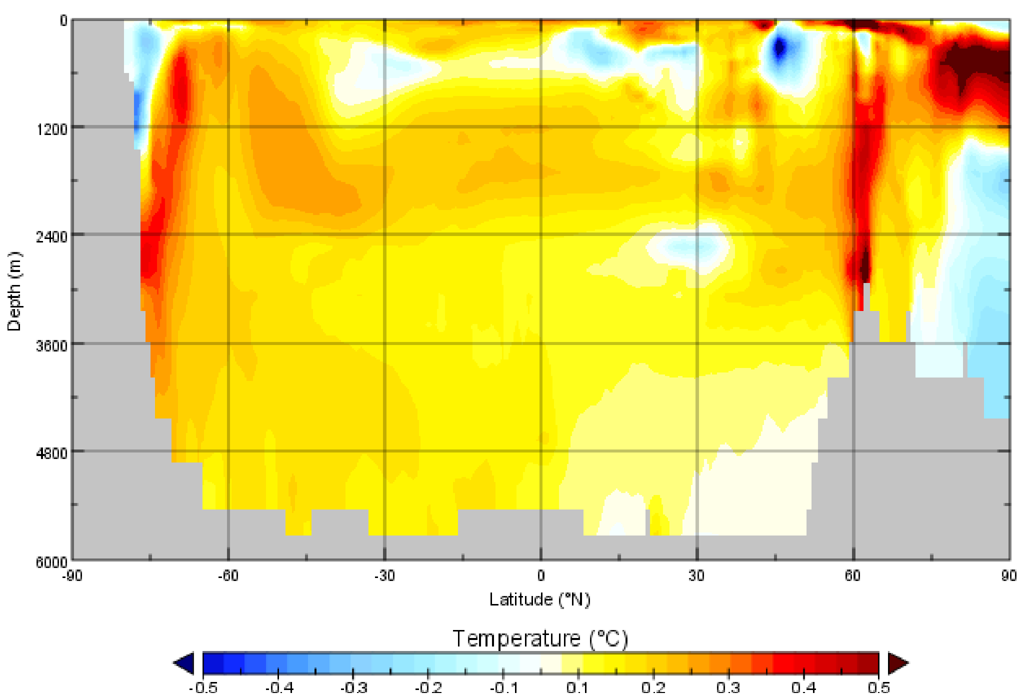

Figure R2. Effect of Greenland Ice Sheet elevation, insolation, and albedo in the 130 kyr BP simulations. Annual mean ocean temperature anomaly (in °C) for LIG-1300 m-alb simulation minus LIG-ctl simulation.

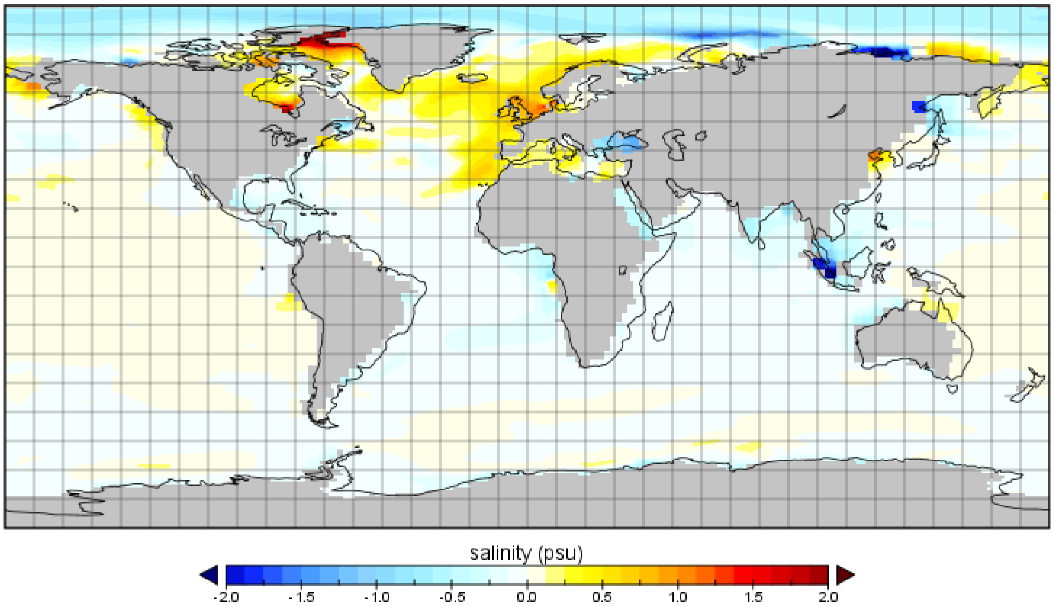

Figure R3. Effect of Greenland Ice Sheet elevation, insolation, and albedo in the 130 kyr BP simulations. Annual mean sea surface salinity (in psu) anomaly for LIG-1300m-alb simulation minus LIG-ctl simulation.

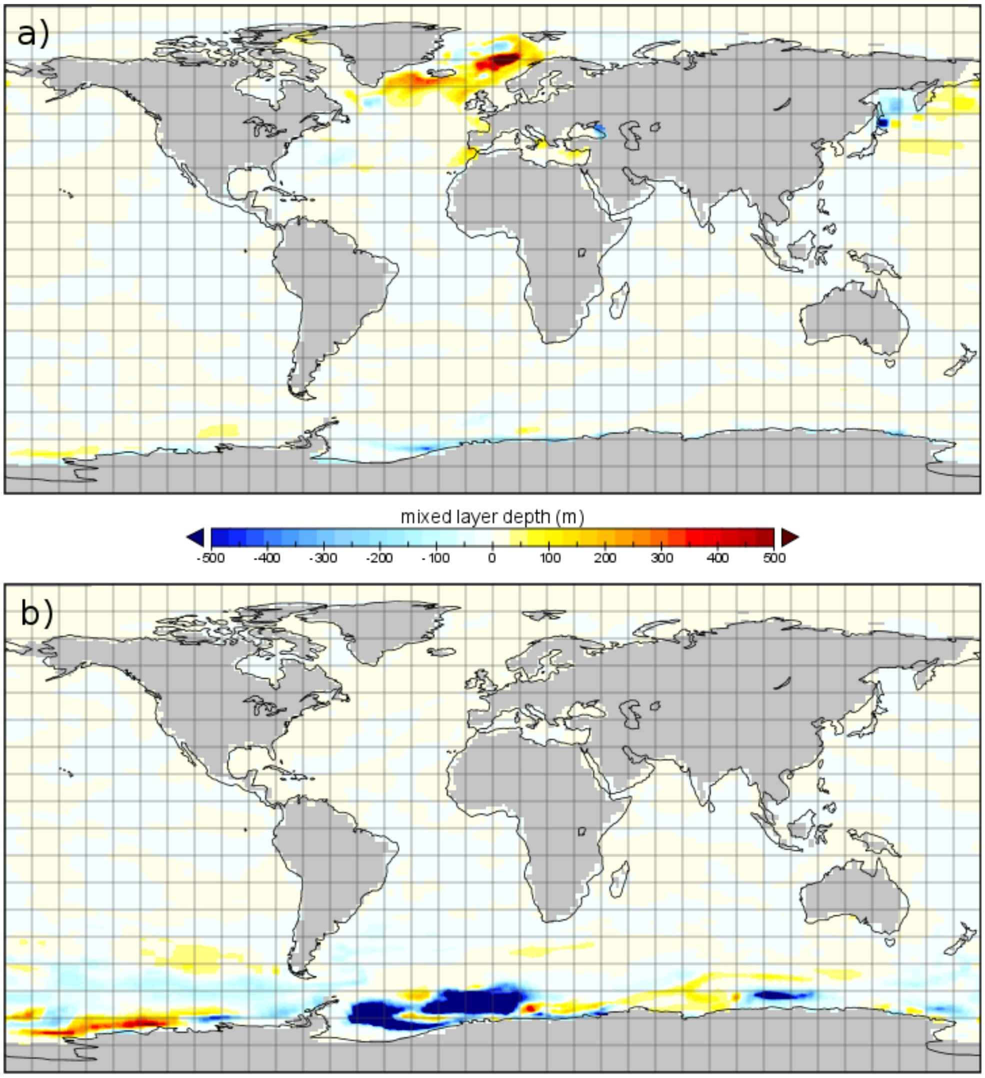

Figure R4. Effect of Greenland Ice Sheet elevation, insolation, and albedo in the 130 kyr BP simulations. Mixed Layer Depth anomalies between LIG-1300m-alb simulation and LIG-ctl simulation for **(a)** December-January-February and **(b)** June-July-August.

Comment:

5) Throughout the manuscript many results are presented and discussed that detail on the impact of GIS elevation and extent changes on the LIG model-data comparison. However, it does not become very clear if overall including these changes improves the model-data comparison. In lines 18-30 of page 952 it appears that the Turney and Jones data are better matched when including GIS changes, while the CAPE data are better match with a PI GIS configuration. The next paragraphs seem to make clear that it is not easily established whether or not including GIS changes improves the model-data

comparison. This point should be made more clear and discussed more thoroughly. For instance, what does it indicate that including GIS changes leads to an improved model-data comparison in locations far away from the GIS itself, while in the Northern Hemisphere high latitudes the comparison does not improve? Why are the figures that show the model-data comparison for the simulations with PI GIS configuration not included in the main manuscript?

Reply

Indeed, one dataset (Turney and Jones, 2010) agrees best with the simulation with reduced GIS, while the other dataset (CAPE Last Interglacial Project Members, 2006) fits best to the control simulation with preindustrial GIS configuration. Furthermore, the newly included dataset from Capron et al. (2014) fits as well best with the control simulation. One explanation is that a reduction in GIS has the strongest influence during local winter, while during summer the changes are very small (Fig. 3 in the manuscript). Therefore, for CAPE Last Interglacial Project Members (2006) and Capron et al. (2014) datasets, which contain a compilation of summer proxies, changes in GIS do not have a strong influence and thus do not improve the model-data comparison. The Turney and Jones (2010) dataset, on the other hand, represents annual mean which is influenced by winter changes, the season when a reduced GIS gives strong anomalies. Therefore, it fits best to the simulation with a reduction in GIS.

Large temperature anomalies caused by changes in GIS elevation are observed only in the southern high latitudes and northern high latitudes close to Greenland, therefore the model-data comparison in the middle and low latitudes is not affected by changes in GIS. Antarctica indicates a warming due to mechanisms and feedbacks mentioned and explained above and in the revised Discussion section, with heat being transported by atmospheric changes (not shown). A reduction in GIS leads to strong warming in the northern high latitudes, which improves the model-data agreement (Fig. 7ab in the revised manuscript). We have made this point more clear in the revised manuscript.

Additionally, we have included the figures with the LIG control simulation (former Figs. S6, S7) in the revised version of the mnaucsript. For an easier comparison, these figures are merged with the corresponding maps that display results from the reduced GIS simulation (Figs. 6 and 7).

Comment:

6) On line 12-13 of page 957 it is mentioned that the changes in atmospheric circulation are small. Nonetheless, afterwards a number of important results are linked to changes in atmospheric circulation. For instance the changes in the AMOC strength (lines 2-7 of page 958) and the cooling west of

Greenland (lines 25-29 of page 958). Including a description of the changes in the atmospheric circulation would greatly improve the manuscript. How do the changes compare to results in the recent publication by Merz et al (2014a, 2014b), see the 'interactive comment' by Andreas Born for more details.

Reply

A description of changes in the atmospheric circulation is included in the revised manuscript, as well as the comparison with results by Merz et al. (2014a). The study by Merz et al. (2014a) indicates a rather localized change in the low level winds due to changes in GIS topography, with no major large-scale changes in the atmospheric circulation. Our study focuses rather on large-scale atmospheric changes. We observe an increase in air circulation west of Greenland and above northern North Atlantic Ocean as well as at other locations.

Minor comments:

Comment:

Line 4 page 934: "...with a notably lower Greenland Ice Sheet...". Isn't it under discussion whether or not this lowering was really 'notably'?

Reply

We have removed the word "notably" from the sentence.

Comment:

Line 21 page 934 (and also line 6 page 938): Why are the transient simulations used to investigate the possible impact of a seasonal bias in the proxy-records?

Reply

The temperatures extracted from the transient simulations are calculated as annual mean as well as summer and winter seasons. Annual and summer means are plotted on maps superimposed by the proxy-based temperatures and on scatter plots, while winter is included only in the scatter plots with the dataset from Turney and Jones (2010) and shows the range between the warmest average of 100 warmest months and coldest average of 100 coldest months. We want to investigate whether summer gives an improvement when comparing the proxy data to maximum LIG warmth, but we also want to provide a seasonal range for a more detailed view on the model-data comparison.

Comment:

Line 9 page 935: Past geologic timescales?

Reply

We have rephrased to “Past time periods”.

Comment:

Line 10 page 935: ’are a useful test bed’. This sounds like there are other test beds as well, are there?

Reply

For the clarity, we have rephrased to “Past time periods provide the means for evaluating the performance of general circulation models”.

Comment:

Line 1 page 936: ’is also considered’. It is not clear what the word ’also’ is referring to.

Reply

We have removed the word “also”.

Comment:

Line 4 page 936: ’at the expense of winter insolation in the tropics’. Do you mean the winter insolation in the mid-high-latitudes of the Northern Hemisphere?

Reply

We have removed this part of the sentence since it is not relevant here.

Comment:

Line 13 page 936: ’is considered to be’. This is perhaps a bit too strong, at least when you are talking about the LIG in general.

Reply

We rephrased to “According to different studies, the GIS was lower [...]”

Comment:

Line 20 page 936: This sentence makes it sound like the GIS is the only possible contribution to the global sea level. Please clarify.

Reply

We do not find this sentence misleading as we do not claim that the sea level was probably higher only due to GIS melting. Only that if GIS partially melted then this would lead to an increase in the sea level.

Comment:

Line 22-23 page 936: This sounds like there is a specific proxy that gives information about the contribution of the GIS in particular to sea level changes. Please clarify.

Reply

We rephrased to "studies based on reconstructions and climate models indicate that [...]".

Comment:

Line 24-30 page 936: It would be helpful for the reader if you could summarize these studies by providing the range of estimates of the contribution of LIG GIS changes to global sea level. Further on in the manuscript these numbers can be compared to the changes that are imposed in the different sensitivity experiments.

Reply

We have summarized the studies that indicate sea level rise due to GIS melting, with a range of +0.3 to +5.5 m. In our simulations, the GIS changes would results in an approximately 3 m increase in the sea level.

Comment:

Lines 14-23 page 937: This paragraph starts out by discussing previous studies that have investigated LIG GIS, these studies don't so please move them to another section for clarity.

Reply

We have split this paragraph in two. The first one covers other studies on changes in GIS during the LIG. It continues with model-data comparison studies that indicate mismatches when reduced GIS is considered. The second paragraph describes model-data comparison studies for the LIG but without changes in GIS, indicating as well a mismatch. Therefore, we consider in our study different boundary conditions in GIS elevation and extent as well as other possible factors that may improve the model-data comparison.

Comment:

Lines 9-11 page 938: I don’t see why this sentence is here. Please remove or move to another part of the manuscript.

Reply

We have removed this sentence.

Comment:

Lines 12-27 page 938: Use this paragraph to make clear what the reader can expect in the remainder of the manuscript. Including a short description of the different simulations that will be presented and what their purpose is with regard to answering the main research questions.

Reply

We rephrased the paragraphs in a more clear and concise way, including the purpose of the model simulations.

Comment:

Lines 20-21 page 939: This line appears to say to models with flux corrections cannot be used to study climate states beyond the present. Please clarify.

Reply

To avoid confusion we have removed from the text “[...], allowing for applications of the model for climate states beyond present. [...]”.

Comment:

Line 26 page 939: Include previous LIG studies.

Reply

We have included references to previous LIG studies.

Comment:

Line 1 page 940: Perhaps include a short description of the orbital forcing of the LIG (130kyPB) to help the reader understand the results. Is the transient orbtital forcing described in the manuscript or depicted in the supplement?

Reply

A short description of the LIG orbital forcing is now included. The transient orbital forcing is not described in the manuscript nor the supplement, but the reference is given.

Comment:

Line 9 page 940: Why use mid-Holocene GHG values?

Reply

The main focus of this study is to quantify the effects of changes in GIS on global temperatures, therefore we did not change the GHG concentrations to early LIG values. It does not follow the preindustrial GHG concentrations from the PMIP2 protocol, as the PI simulation (Wei et al., 2012) has been produced after we have performed our LIG simulations.

Comment:

Line 11 page 940: Make clear why increased CH4 levels are used. It appears from table 1 that the CO2 levels are also slightly different. Perhaps the description of the different GHG forcing can be moved to the end of this paragraph.

Reply

The reason for using increased CH_4 levels are given in the answer of the General comments no. 2). The difference in the CO_2 levels can be considered insignificant. We have moved this sentence at the end of the paragraph.

Comment:

Line 16 page 940: Include a description of how these GIS changes translate into meters sea level equivalents and how this compares to literature estimates.

Reply

We have included a short description and a comparison with values proposed by other studies.

Comment:

Line 12 page 941: Perhaps move the description of the transient simulations to here?

Reply

We have moved the description of the transient simulations as suggested.

Comment:

Line 4-5 page 942: Why is a Holocene simulation included?

Reply

We include a Holocene transient simulation as a reference with respect to LIG transient changes, for orientation purpose and to display the differences between the present and last interglacial.

Comment:

Line 7 page 942: what kind of near equilibrium state? What are the forcings of this equilibrium simulation?

Reply

The "near-equilibrium state" refers to the adjustment of the climate system to the prescribed forcings. Is called "near-equilibrium" because the ocean needs a longer time to adjust than the time length of our simulations. The transient simulations are started using the sensitivity simulations analyzed in this manuscript, namely: LIG-ctl simulation was used for starting the transient LIG-ctl-tr simulation, LIG-x0.5 for LIG-x0.5-tr, LIG-1300m-alb for LIG-1300m-alb-tr, and LIG-GHG for LIG-GHG-tr. The forcings for all these equilibrium simulations are given in Table 1 of the manuscript. The forcings for the equilibrium simulation used for starting the HOL-tr transient simulation are not given because this equilibrium run is not included in the manuscript and thus we did not consider necessary to provide this information.

Comment:

Lines 19-28 page 942: Are lines 19-20 discussing the definition for the equilibrium experiments and the other lines for transient simulations? Are the 50(100) coldest or warmest months consecutive months or taken from throughout the LIG? If the latter is the case, how does this relate to the dating uncertainty in proxy-records that the authors try to capture with this method?

Reply

The first sentence refers indeed to the equilibrium simulations and the rest to the transient. We rephrased for clarity. The coldest and warmest 50 months from the equilibrium runs are calculated from consecutive years, as we always use only the last 50 years of the equilibrium simulations. In the case of the transient simulations, the 100 coldest and warmest months are calculated also from 100 consecutive years, but as a running average. This method creates a series of subsets of 100 years (e.g. year 1 to year 100, year 2 to year 101, year 3 to year 102, and so on), and then calculates the average of each subset. The subset that shows the highest/lowest average is taken as the maximum/minimum LIG warmth. This method is used in order to filter out internal variability.

Comment:

Lines 4-15 page 943: One are the CAPE temperature reconstructions considered summer temperatures and the Turney and Jones temperature reconstructions annual mean. Are they in general different types of proxies or is it related to the different geographic locations or a different interpretation of the proxies?

Reply

The CAPE Last Interglacial Project Members (2006) temperature reconstructions are a compilation of summer proxy-based temperatures selected by the authors of the respective paper, as they wanted to focus on summer during the LIG. Each proxy site is published by different authors and all the references are given in Tables 1 and 2 in CAPE Last Interglacial Project Members (2006). Turney and Jones (2010) is as well a compilation of records published by other authors, but of annual mean proxy-based temperatures.

Comment:

Line 4-16 page 944: what is the direct impact of the changes in GIS elevation on local temperatures through the lapse rate and how does this compare to the total simulated temperature changes?

Reply

The lapse rate is actually negligible, the "climate effect" being the dominant one (Fig. R5). We have calculated the "climate effect" by extracting the temperature from the simulation with reduced GIS (LIG-x0.5) at the height of the preindustrial GIS, for each given grid cell. From this interpolated temperature we have extracted the surface temperature from the simulation with preindustrial GIS (LIG-ctl). The temperature over the glacier boundary layer is increasing with height until a specific elevation after which it is decreasing. The increase in temperature with height is larger in the simulation with reduced GIS than in the control simulation.

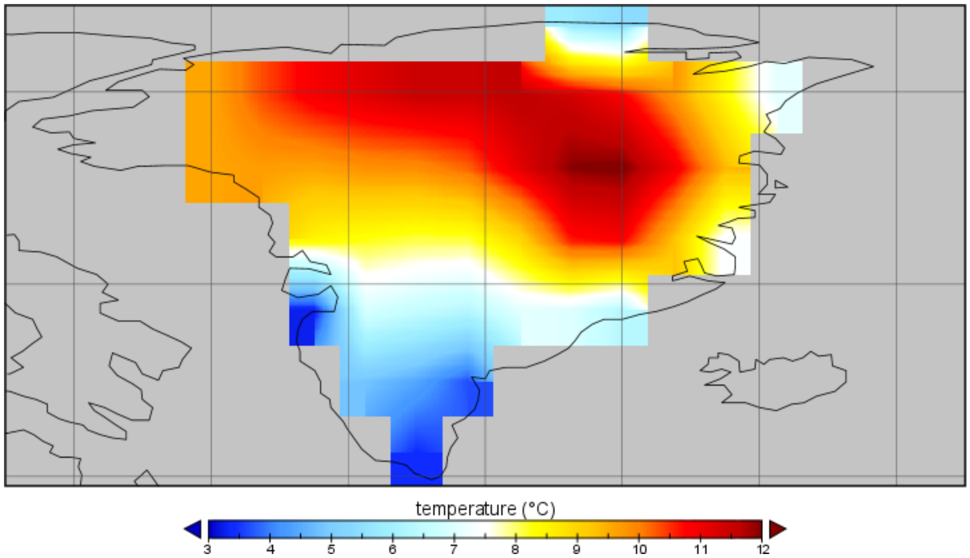

Fig. R5 Temperature anomaly representing the "climate effect". Temperature derived from the simulation with half GIS (LIG-x0.5) interpolated at the height of preindustrial GIS minus the surface temperature derived from simulation with preindustrial GIS (LIG-ctl).

Comment:

Line 15 page 944: Is the 0.5Sv change significant?

Reply

The 0.5 Sv change can be considered minor.

Comment:

Line 15 page 945: Is the 0.2Sv change minor or perhaps even smaller, say negligible?

Reply

The 0.2 Sv change is negligible.

Comment:

Line 22 page 945: is this +0.24C value the same for NH, SH and globally?

Reply

Yes, the average is the same for Northern and Southern Hemispheres and globally.

Comment:

Line 21 page 947: What is the impact of the choice in alignment between the LIG and the Holocene. In other words, do the described differences between the two periods point towards differences in terms of the response of the climate to changes in the forcings, or do the differences appear because of the choices made in the alignment?

Reply

The choice in alignment is somewhat arbitrary. Differences between the two interglacials are caused by the climate's response to changes in the prescribed forcings.

Comment:

Line 21 page 947: are any of the results presented here discussed in the discussion section?

Reply

These results were also discussed in the Discussion section of the original manuscript, but for simplicity and a more concise story we have decided to remove these results and discussion from the revised version of the manuscript and describe only shortly the importance of these simulations in the story, namely to determine the maximum LIG warmth used in the model-data comparison.

Comment:

Line 6 page 948: are these temperature changes per ky? Per 10ky?

Reply

The trends have been calculated per 15 kyr.

Comment:

Line 7 page 950: This section is very long, perhaps use subheading to improve the readability.

Reply

We have introduced subheading in the revised version of the manuscript.

Comment:

Line 14 page 951 to line 17 page 952: Try to structure the description of the results, try not to jump back and forth between different geographical regions.

Reply

The description of the results is structured based on time slices rather then geographical regions. First, we present results from the 130 kyr BP simulation, describing the comparison in some key regions. Afterwards, the model-data comparison focuses on TS anomalies at maximum LIG warmth, again presenting results from some key regions. However, for more clarity we have rephrased parts of the paragraphs.

Comment:

Line 10 page 953: What does this 0-10C range mean? Please clarify.

Reply

The CAPE Last Interglacial Project Members (2006) proxy data compilation does not contain fixed temperatures for most sites but rather temperature intervals. We extract from these specific intervals, the temperatures that fit best to the simulated temperatures.

Comment:

Line 16 page 953: what do the summer minimum and summer maximum LIG warmth mean? What is their relationship to the uncertainty in the interpretation of the proxy-records?

Reply

The summer minimum and summer maximum LIG warmth are calculated from the respective transient simulation. First, we have calculated the warmest month of each model year between 130 and 120 kyr BP. Then, we have calculated the running average with a window length of 100 model years and selected the warmest average of 100 warmest months which represents the summer maximum LIG warmth. For the summer minimum LIG warmth, we take the coldest average of 100 warmest months average. We use this method because the CAPE Last Interglacial Project Members (2006) proxies are considered to represent summer at the peak LIG warmth and we want to determine whether this approach increases the model-data agreement. The minimum summer LIG warmth is additionally calculated in order to have a temperature interval for the comparison.

Comment:

Line 29 page 954: 'not as good'. Can the comparison for terrestrial data be considered as good?

Reply

We have rephrased.

Comment:

Lines 15-27 page 955: In this methodology, do you consider every site individually when determining the season for which the simulated temperatures fit the reconstructions best? If so, is this realistic? Wouldn't one expect some kind of geographical pattern in the seasonal bias of the proxy records?

Reply

The simulated temperature is extracted at the location of each given proxy. A geographical pattern is indeed expected, though in some regions is more difficult to determine. Other studies on model-data comparison that consider seasonal biases have the same assumptions that there are regions that have rather a mixed signal (e.g. Lohmann et al., 2013).

Comment:

Lines 4-10 page 956: why is the orbital forcing not described earlier in the manuscript?

Reply

We have moved the description of orbital forcing to the Data and Methods section.

Comment:

Lines 7-9 page 956: in which season did the low latitudes receive less insolation or is it an annual mean signal?

Reply

In the annual mean, the effect of obliquity on insolation in the tropics is minor. Yet, there is still an effect of obliquity on the tropical climate (Bosmans et al., 2015).

Comment:

Line 8 page 956: shortly explain why the calendar shift only has minor impact on the results presented here.

Reply

The calendar shift has a minor effect here because we calculate the summer and winter seasons by extracting the warmest and coldest month rather than June-July-August and December-January-February averages.

Comment:

Lines 22-24 page 956: 'hinting to'. Please shortly clarify this point. What kind of processes/feedbacks are involved. And is this true for both hemispheres?

Reply

Here, we refer to positive feedbacks such a sea ice-albedo feedbacks, which have an influence in both hemispheres.

Comment:

Lines 14-15 page 957: how do the easterlies impact the Barents Sea? Please clarify.

Reply

Actually, Barents Sea does not fit in that sentence. We have rephrased for clarification.

Comment:

Line 24 page 957: include a better description of the AMOC changes in the different experiments. In the LIG the AMOC weakens compared to PI? And the lowering of the GIS partly counteracts this weakening? Explain why the AMOC changes are simulated, especially since the authors connect the changes to important temperature changes in the high latitudes of the southern hemisphere.

Reply

The AMOC during the LIG is indeed weaker than the PI, but changes in GIS decrease the difference between last interglacial and preindustrial AMOC values. This mechanism is explained in the answer to Comment no. 4) from General comments.

Comment:

Line 10 page 958: What could be the cause of the different response of the AMOC in the studies by Otto-Bliesner et al. (2006) and Bakker et al. (2012)?

Reply

Both studies consider, in addition to changes in GIS, a relatively strong freshwater flux into the North Atlantic Ocean, a factor that is not included in this study. Such a freshwater input would lead to a weakening of the AMOC.

Comment:

Line 17 page 958: Bakker et al. (2012) find that a lowering of the GIS leads to a small additional weakening of the AMOC. Please discuss.

Reply

A short explanation is added in the discussion of the revised manuscript.

Comment:

Lines 19-26 page 959: The description of the simulations that do and do not include interactive vegetation is confusing. On line 12 of page 941 LIG-GHG simulation is said to be the only simulation with fixed PI vegetation. How does this relate to the simulations that are discussed here (LIG-GHG-tr and LIG-ctl-tr)?

Reply

In the Data and Methods section, it is indeed written that the only simulation with fixed PI vegetation is LIG-GHG, but it refers to the equilibrium simulations only, since the transient simulations are not yet introduced. Later, when the transient simulations are presented it is written that the LIG-GHG-tr is the only simulation with fixed PI vegetation, and that refers to the transient simulations only (see Page 942 Lines 15-17 in the original manuscript). The equilibrium simulation LIG-GHG was used for starting the LIG-GHG-tr transient simulation, and both have a fixed preindustrial vegetation. LIG-ctl-tr (and all the other transient simulations were run with dynamic vegetation). However, we have rephrased in order to avoid confusion.

Comment:

Lines 12-14 page 960: Do they find a linear relation between temperature and insolation for all seasons and latitudes? Please clarify.

Reply

Bakker et al. (2013) find a linear relation between changes in insolation and temperatures for both summer and winter and for all latitudes. There are however some exceptions. In northern high-latitudes, the winter temperature changes result mainly from sea-ice related feedbacks and are described as highly model-dependent. In southern middle to high latitudes, winter temperatures are strongly affected by changes in GHG concentrations.

Comment:

Lines 20-22 page 960: 'offer a bandwidth of possible temperatures'. Is that an aim of this study? If so please introduce it as such in the introduction.

Reply

This is not a particular aim of our study, rather an additional result.

Comment:

Line 7 page 961: 'related to sea ice'. Or are the changes in sea ice related to the changes in temperature? Please clarify.

Reply

It is difficult to unravel these effects in a coupled climate model, due to the fact that both influences interact simultaneously.

Comment:

Line 18 page 961 (and also 19-21 page 962 and lines 12-15 of page 965): I don't think that determining which model performs best on a particular model-data comparison in a particular region, without discussion the mechanisms behind it, is scientifically relevant.

Reply

The sentence from Line 18 page 961 does not refer to which model performs best but to the fact that COSMOS simulates much higher temperatures over Greenland than the ice core-based temperatures from CAPE Last Interglacial Project Members (2006) dataset. We have removed the other two sentences.

Comment:

Lines 20-24 page 961: Not sure how this fits into the general topic of this section. Please clarify.

Reply

We have removed this part since is not so relevant here.

Comment:

Lines 24 page 961 to line 25 page 962: This is an important section. Make clear what the results of this manuscript tell us about how changes in the GIS impact the model-data fit, how this compares to previous model results and how this compares to for instance ice core data.

Reply

We have reorganized this paragraph.

Comment:

Lines 16-20 page 963: I'm not convinced that the results presented here actually allow you to make this statement. Please clarify.

Reply

For an easier comparison, we have included in a single panel the model-data comparison of simulation with reduced GIS (Fig. 7a, b) and preindustrial GIS configuration (Fig. 7c, d). This figure clearly shows that there are regions in the high latitudes that present an improvement in the model-data comparison when reduced GIS is considered. Moreover, the RMSD values are smaller in the case of comparison of the Turney and Jones (2010) proxy-based temperatures to the simulation with reduced GIS (Table S2 in the Supplementary material of the revised manuscript) than to the simulation with preindustrial GIS elevation.

Comment:

Lines 25-29 page 963: What could such long-term feedbacks be for the LIG? Probably melting of the GIS is one of them, but what other processes do the authors suggest are missing in their simulations? More generally, what should be included in terms of forcings and long-term feedbacks in order to improve future model-data comparison for the LIG?

Reply

The long-term feedbacks missing in our climate model refer for example to the state of the lithosphere which has not been yet implemented. A coupled ice sheet model and the biogeochemistry are already implemented in the COSMOS but are relatively new tools, and we did not include them in our LIG simulations because running for example the carbon cycle and the ice sheet into equilibrium would take a very long computational time. Additionally, other factors like glacial memory effect is not well represented and cannot be fully reproduced by the models.

Comment:

Line 29 page 964 and lines 1-7 page 965: Make more clear how the presented data support the notion that the comparison of the proxy-data compilation of Turney and Jones with the COSMOS LIG climate simulations is best when simulated annual mean temperatures are used. How certain are the authors on this point? This results appears to be in large contrast to previous studies, but if indeed the case, an important finding. Please clarify.

Reply

In all considered cases (PI GIS, GISx0.5, GIS-1300m, and GIS-1300m and albedo, at 130 kyr BP, 125 kyr BP, and maximum LIG warmth) the best agreement occurs always when simulated annual mean anomalies are considered. These results are supported by the RMSD values given in Table S2 in the Supplementary material of the revised manuscript. The terrestrial proxies from Turney and Jones (2010) are described as representing annual mean at the maximum LIG warmth and we find indeed the best fit for simulated annual mean TS at maximum LIG warmth in the simulation with reduced GIS (LIG-1300m-alb). We have made the point more clear in the revised manuscript.

Comment:

Line 7 page 967: following on the previous point, isn't 'in fact' too strong a statement?

Reply

We have removed "in fact" from the sentence.

Comment:

Line 1 page 976: In this section as well as in the conclusions, it is discussed how certain simulations and seasons provide the best model-data temperature comparison. What is the benefit of describing how one scenario fits one location while another scenario fits another location. They can't all be true! For instance if the extent of the GIS changed, so did the albedo in those locatioins. And especially considering GHG changes, we know they changed so doesn't an improved model-data comparison in case GHG changes are neglected indicate an improvement for the wrong reason? Please elaborate.

Reply

This is a sensitivity study that considers only one factor rather than a full representation of the LIG climate. The model-data comparison is firstly performed in order to have a feeling on the order of magnitude of LIG temperatures. Future studies taking into account all climatic factors of the LIG should be considered.

Regarding the GHG concentrations, they indeed changed over time, but between the 130 kyr BP time slice and the maximum LIG warmth the differences are in the astronomical forcing which lead to an improved model-data comparison, independent on the size of GIS.

These changes like orbital and GHG concentrations are identical in all LIG transient simulations (except LIG-GHG-tr), meaning that if there is a difference in the model-data comparison between the different simulations, the reason for this difference is the configuration of the GIS since all the other forcings are identical.

For a shorter and more concise story we have removed this section from the revised version of the paper, and also the part in the Conclusions that summarize the results of this particular section.

Comment:

Lines 3-11 page 968: It appears that even if one takes into account a large number of uncertainties, the model-data comparison is still rather poor.

Reply

Indeed, taking into account several uncertainties does not completely solve the model-data disagreement but this way we manage to at least partly reconcile the model-data discord.

Comment:

Lines 5-10 page 969: It is concluded that a reduction in the GIS elevation and extent improves the agreement between model and data. How conclusive are the results? Especially since in the next line they mention that in 1 out of 2 data sets that are used, the opposite is found.

Reply

A reduction in GIS elevation and extent improves the agreement between model and data in the case of Turney and Jones (2010). We have rephrased for more clarity.

Comment:

Lines 21-23 page 969: Where does this statement on climate sensitivity come from? Is it discussed at all in the manuscript? How can one expect to be able to study climate sensitivity in a model experiment in which CO2 is not even changed?

Reply

That indeed is not a correct formulation. We have rephrased to “[...] interglacial climate change”.

Comment:

Lines 24-25 page 969: ’Better representation of the climate models’? Please clarify.

Reply

Rephrased to: “a better representation of the LIG climate in earth system models”.

Comment:

Line 27 page 969: Is it useful according to the presented results to perform transient simulations including transient changes in GIS elevation and extent?

Reply

Transient simulations with transient changes in GIS are needed for a more realistic representation of the climate at any point during the LIG. Such studies would be useful for a model-data comparison of LIG temperature evolution.

Comment:

Table 1: are the simulations LIG-GHG, LIG-125k and GI mentioned at all in the manuscript?

Reply

We have removed the GI simulation. LIG-GHG simulation is kept in the Supplementary material in order to show that the differences between the GHG concentrations that we have used in our simulations do not have large effects on TS. The LIG-125k is mentioned in the Discussion of the revised manuscript, when a comparison with Otto-Bliesner et al. (2013) study is included, and also a comparison with Capron et al. (2014).

Comment:

Table 2: How are summer and winter defined? Please repeat this information in the caption.

Reply

We have added this information in the caption.

Comment:

Figure 2: Why are the results of the LIG-ctrl simulation not shown for comparison?

Reply

The results of the LIG-ctl simulation are already included in the comparison. Figure 2 displays TS anomalies between the simulations with changes in GIS (LIG-x0.5, LIG-1300m, LIG-1300m-alb) and the control simulation LIG-ctl.

Comment:

Figure 2 (and others): I find the color-sceme that is used (blue to red) a bit misleading. It nicely shows the difference between positive and negative, but the differences between the different shaded of blue/red are very small and make, for instance, the model-data comparison in figures 8 and 9 look much better than figure 10 shows. Please clarify.

Reply

We have kept the blue-to-red colorbar, but changed the colors in a way that it is easier to distinguish between different shades.

Comment:

Figure 5: Which one of the presented simulations does not include interactive vegetation changes? How large is the impact?

Reply

The simulation with LIG-GHG-tr does not include dynamic vegetation changes. The impact is significant, as it counteracts the effects of the GHG concentration changes which are mostly lower than the fixed GHGs in the LIG-ctl-tr. Therefore, we expected lower temperatures in LIG-GHG-tr, but actually indicates warmer temperatures. The only difference between these two transient simulations, other than GHG concentrations, is the vegetation which is dynamic in the LIG-ctl-tr, meaning that the vegetation leads to a cooling in the Northern Hemisphere.

Comment:

Figure 5: 21 model years so 210 orbtital years? Please mention in caption.

Reply

We have added in the caption: "21 model years representing 210 calendar years."

Comment:

Figures 5-7: why is there no focus on the SH when the transient results are discussed?

Reply

We have created figures only for the Northern Hemisphere because of the load of data and information that led already to a long manuscript. We have kept in the revised manuscript only the northern high latitudes for the same reason. Furthermore, the influence of GIS is the strongest in the Northern Hemisphere, so we decided to leave for the moment the Southern Hemisphere out of the story.

Nevertheless, the transient data from the Southern Hemisphere is used in the model-data comparison of Turney and Jones (2010) proxy compilation.

Comment:

Figures 8, 9 and 10: Is the LIG-1300m-alb or the LIG-1300m-alb-CH4 simulation presented here?

Reply

In these figures, simulation LIG-1300m-alb is used. This information is already mentioned in the respective figure captions.

Comment:

Figure 10: I find this caption rather confusing. Is (b) about annual means and (c) about the seasonal range? What do the vertical bars and the gray bars indicate?

Reply

We have reorganized the caption for more clarity. In (b) and (c), the dots are identical representing annual mean. The only difference is that in (b) the vertical bars indicate the range between the maximum and minimum LIG TS with respect to annual mean, while in (c) they show the range between the maximum and minimum LIG TS with respect to summer (warmest month) and winter (coldest month), respectively. There are no gray bars, where it appears gray there is a displaying problem.

Comment:

Figure 11: Why is the period 130-120 used?

Reply

We use these time interval because the maximum LIG warmth occurred within this interval, not after 120 kyr BP.

Comment:

Figure 11:Why are the proxy locations depicted?

Reply

We have removed the proxy locations, as indeed do not add any information to the story.

Comment:

Supplementary information: Where can one find the figure captions?

Reply

The supplement figure captions are in the file “Pfeiffer_and_Lohmann_supplement.doc” in the “.zip” file containing the supplementary figures.

Technical comments

Comment:

Line 6 page 934: make clear that these are equilibrium simulations.

Reply

Done.

Comment:

Line 2 page 935: ’are the projections’

Reply

We have rephrased to “is the computation of future climate projections”.

Comment:

Line 7 page 935: change to “needs to be tested (e.g. Braconnot et al....)”

Reply

Done.

Comment:

Line 14-16 page 935: Please rephrase.

Reply

We have rephrased.

Comment:

Line 13 page 936: ’during the LIG compared to PI’

Reply

Done.

Comment:

Line 13 page 938: equilibrium simulation.

Reply

Done.

Comment:

Line 14 page 938: Clarify what is considered the ’entire LIG’.

Reply

We removed that part since it does not fit anymore to the sentence as it described equilibrium simulations.

Comment:

Line 18 page 938: .’physical characteristics’ sounds a bit critical. Consider rewording.

Reply

The paragraph is rephrased and reorganized. We refrained from using “physical characteristics”.

Comment:

Line 26 page 938: ’timing uncertainty’?

Reply

We have added “uncertainty”.

Comment:

Line 6 page 949: Not sure whether the word realization is appropriate when discussing different simulations with different forcings rather then different ensemble members forced by the same scenario.

Reply

We have removed the word “realization”.

Comment:

Line 19 page 950: Isn’t Great Britain part of Europe?

Reply

We have removed “Great Britain”.

Comment:

Line 2 page 951: ’the sign is generally comparable’. This sounds strange since the sign can only be the same or not.

Reply

We have replaced “comparable” with “the same”.

Comment:

Line 8 page 956: high latitudes of the Northern Hemisphere.

Reply

We have added “of the Northern Hemisphere.” The part of the paragraph describing the orbital forcing is now moved to Data and Methods section.

Comment:

Line 10 page 956: ’in the early LIG’

Reply

Done.

Comment:

Line 9 page 963: ’presents as well’ perhaps ’also presents’.

Reply

Done.

Comment:

Line 12 page 963: capture at most or simply remove the word ’mostly’.

Reply

We have removed the word “mostly”.

Comment:

Line 17 page 963: is the hyphen supposed to be there?

Reply

Yes.

Comment:

Figure 11: It appears there is a space in Turney.

Reply

The sentence containing this reference is removed because the circles on the maps have been also removed.

References:

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Reply to Emilie Capron

1. Summary and general comments

M. Pfeiffer and G. Lohmann present a sensitivity study that aims at quantifying the contribution of the height and extent on the Greenland Ice Sheet (GIS) to the Last Interglacial (LIG) warmth based on a wealth of snapshot and transient simulations performed with the Community Earth System Models (COSMOS). They confront the simulated Surface Air Temperature (SAT) with reconstructed SAT based on marine and terrestrial records and they discuss the observed model-data mismatch. They argue that this mismatch can be reduced when taking into account the seasonal bias of the proxy records and the bias due to uncertainties in the proxy record chronologies and, subsequently, the LIG maximum warmth timing.

This sensitivity study is an interesting contribution with implications relevant to the climate and paleoclimatic communities (both model and data): Evaluating the performance of Earth System Models under the warmer-than-present-day LIG and better constraining the role and the configuration of the Greenland Ice Sheet under such context are key issues of particular relevance in the context of our current and future warming world.

The authors have run numerous simulations and provide a very thorough description of the new simulations. I really appreciate the huge amount of work that this represents. Unfortunately, it results in a very long paper which is difficult to read while other aspects of the paper also need improvements and clarifications. As a result, I can only recommend the publication of this manuscript in Climate of the Past after some major revisions. I will be happy to read the next version of the manuscript and I have listed below comments and suggestions that the authors should consider when preparing

Reply

We thank Emilie Capron very much for the detailed and valuable comments on our manuscript, which help us to increase the quality of the paper. We agree that the manuscript in its published form is too long and lacks focus. Therefore, we have shortened it in the revised version and removed some analysis that was not directly related to the main topic of the paper.

Note: We have corrected in the whole manuscript the terms “surface air temperature (SAT)” and replaced it with “surface temperature (TS)”, as in our analysis we actually use surface temperature (TS) which is a combination of land surface temperature and sea surface temperature.

I have three main comments:

Comment:

1. As suggested in the title and in the introduction, the purpose of the paper is to quantify the contribution of the GIS to LIG warmth. However, my feeling is that at the end of the paper, the reader is not left with a precise message answering the purpose of the paper.

Reply:

We have tried in the revised version of the manuscript to write it in a way that the message becomes more clear by the end of the paper.

Here are some suggestions that should participate in resolving this issue:

Comment:

- Up to 15 simulations have been run leading to model outputs presented in 11 figures in the main manuscript and 19 figures in the Supplementary Material. I think that the authors should re-consider if all the simulations and outputs they show are necessary and participate in improving our understanding of the climatic processes during the LIG and the role of the Greenland ice sheet. In particular, I am not sure I understand why the simulation testing the methane effect is relevant in the context of this study (see comments in the "specific comment" section). Also, is it really necessary to leave the simulations for 115 ka since, as far as I understand, they are hardly discussed in the manuscript?

Reply

The reason for including a simulation with different CH_4 values is indeed not clear in the original manuscript, but an explanation is added in the revised version. The LIG-1300m-alb-CH_4 simulation has been performed in order to have one LIG simulation that has identical GHG concentrations as the PI simulation (Wei et al., 2012) which was run with concentrations as proposed by PMIP2. This simulation is needed in order to be able to quantify the combined as well as separated effects of insolation and changes in GIS and albedo on global climate, without any changes in GHG concentrations since this is not the focus of this study. The effects of different CH_4 values are displayed in Fig. S2 in the Supplementary material of the initial manuscript, but this figure is removed from the revised version since is indeed not of relevant importance to the main story. However, the LIG-1300m-alb-CH_4 simulation is not used in the model-data comparison because all other LIG experiments with reduced GIS do not have identical GHG values like PI simulation from Wei et al. (2012). Therefore, in order to be consistent in the model-data comparison of the proxies with different LIG simulations, we use the simulation LIG-1300m-alb since it has identical GHG concentrations with those used in the other simulations that consider a reduction in GIS, as well as in the LIG-ctl simulation. We, therefore, keep the LIG-1300m-alb-CH_4 simulation in the revised manuscript in order to be able to quantify the exclusive effects of insolation and changes in GIS configuration on the global climate.

We have removed some of the simulations that do not directly relate to the main topic. The GI (115 kyr BP) and HOL-x0.5 (6 kyr BP) simulations are removed in the new version of the manuscript.

Comment:

- This big number of simulations results in a Result Section which is too long and too descriptive. I find it hard to read and difficult to extract the key messages. A big effort of synthesis would be necessary to propose a more concise description of the results (i.e. the authors could focus on similarities and differences between simulations in some key regions). I think it would be very useful if the authors could provide a more critical point of view on the various simulations they present and discuss in a clearer way for instance which extent and height to the Greenland ice sheet leads to the results the closest to the data and also what should be the most appropriate simulation to represent the LIG climate.

Reply

We have shortened the Results section and structured it in a more concise way.

The question regarding which size of GIS yields the best model-data comparison is answered in the form of three tables added in the Supplementary material and discussed in the revised version. The three tables contain the RMSD values between the three different datasets used in this study (CAPE Last Interglacial Project Members, 2006; Turney and Jones, 2010; Capron et al., 2014) and the simulations with different GIS configurations calculated at different time slices and for annual mean and local summer. We decided to add tables rather than fully include it in the manuscript for two reasons. Firstly, due to the large amount of data, creating model-data comparison maps for each simulation would results in a too long manuscript that would again lack focus. Secondly, the purpose of this manuscript is not to determine which GIS size yields the best model-data agreement, but to determine the influence of GIS changes on global climate during the LIG. The reason for choosing only one reduced GIS configuration in the model-data comparison in the original manuscript is because both proxy datasets from CAPE Last Interglacial Project Members (2006) and Turney and Jones (2010) indicate a significant warming in the Northern Hemisphere, therefore we considered to take the reduced

GIS simulation which indicates the strongest warming in order to increase the model-data agreement. From the tables is also clear that the main conclusion did not change since the proxy-based temperature anomalies by CAPE Last Interglacial Project Members (2006) indicate the best agreement with the simulation with preindustrial GIS (LIG-ctl), while the Turney and Jones (2010) dataset fits best to the simulation with reduced GIS and changes in albedo (LIG-1300m-alb). For the new proxy-based dataset that is included in the revised version of the manuscript (Capron et al., 2014), we find the best model-data comparison for summer at 125 kyr BP in the LIG-1300m-alb simulation. However, this result is not conclusive with respect to the size of GIS because we do not have other GIS configuration simulations for this time slice.

It is not easy to indicate what should be the most appropriate simulation to represent the LIG climate. The preindustrial configuration of GIS in the LIG-ctl simulation is not considered the most "realistic" since there is strong evidence that the GIS elevation and extent were lower during the LIG than the PI. The main question is what was the real height of GIS during the LIG, a subject that is still under debate. In our study, we decided to consider simulating a more dramatic change, namely about half its preindustrial elevation. The most "realistic" simulation with GIS reduction is LIG-1300m-alb because the albedo is adjusted accordingly where the ice is removed, though one must be cautious since as we already mentioned the reduction of GIS in this simulation is dramatic. The other two simulations with a different representation of the GIS were run with ice albedo everywhere above Greenland, though there were ice-free areas during the LIG. We use a rather simplistic representation of the GIS in our model simulations, as our main interest is to quantify the effects of changes in GIS on the global climate rather than local.

Comment:

-This comment applies as well for the discussion section. It should be shorter and more to the point. But in addition, I think the paper would be improved with a more critical (rather than descriptive) comparison with other published works in order to better highlight its added value.

Reply:

We have shortened the Discussion section and provide a more concise discussion of our results.

Comment:

2. My second comment concerns the comparison of their model results with existing LIG data

synthesis. The authors neither use or mention the recent data synthesis for the LIG from Capron et al. (2014) combining ice core and marine sediment records covering the high-latitude regions (latitudes above 40°). This new data synthesis is the first one providing a coherent temporal framework between records and thus accounting for the non-synchronicity between records from different regions during the interval 130-115ka rather than presenting one single snapshot representing the LIG maximum warmth such as in previous work. These time series represent appropriate targets for transient simulations. In this paper, we also built 4 time slices at 115, 120, 125 and 130 ka describing SAT and that represent also improved target for snapshot simulations for these time periods.

The authors should consider using this improved data synthesis to discuss their climate simulations. I might be missing information but from what I can extract from their conclusions, the main outcomes of the studies seem to be rather similar to the ones from previous studies, i.e. although a reduction in GIS elevation and extent improves the agreement between model and data, the simulated SATs underestimate the temperature changes indicated by the proxy reconstructions. I think that confronting the simulations with the new datasets (for the high latitude regions) could add an additional dimension in the novelty proposed in this paper. In addition, it provides information about Greenland and Antarctica from ice cores while at the moment, the authors do not discuss these regions in term of model-data comparison.

The authors should not hesitate to contact me. I will be happy to answer to any questions they could have regarding this new data synthesis.

Reply:

We thank Emilie Capron very much for providing us with the new proxy-based dataset (Capron et al., 2014). It is now included in the new version of the manuscript. However, due to the large amount of data we have chosen to include only the temperature anomalies for the 130 and 125 kyr BP time slices in our model-data comparison. Since the focus is on the 130 kyr BP, we have included the 125 kyr BP in the Supplementary material. However, we find a best agreement for 125 kyr BP, though we cannot conclude whether a reduction in GIS contributes to the agreement, since we do not have other simulations with different GIS configurations for this time slice. We can only compare different GIS changes for the 130 kyr BP time slice. In these simulations, the best fit occurs when the marine proxy-based temperature anomalies are compared to LIG-ctl simulation. A reduction in GIS leads to a small warming in the North Atlantic Ocean due to an increase in the Atlantic Meridional Overturning Circulation (AMOC) which transports more heat northwards. Since most of the records are located in the North Atlantic Ocean and most show a negative anomaly with respect to the present, a reduction in GIS does not improve the model-data comparison. However, the differences in TS between the preindustrial GIS and reduced GIS simulations are rather small in the North Atlantic Ocean. In general, COSMOS seems to simulate cooler temperature anomalies as compared to the CCSM3 and HadCM3 climate models (Capron et al., 2014). This is probably caused by the GHG concentrations which are higher in the CCSM3 130 kyr BP simulation than in our COSMOS 130 kyr BP simulations. However, HadCM3 indicates as well warmer anomalies than the COSMOS, though the GHG concentrations are smaller in HadCM3. One factor that may counteract the effect of GHGs is the vegetation which is dynamic in our simulations. We find a similar response in our transient simulations when we compare LIG temperature evolution from two simulations with and without dynamic vegetation. Though the GHG concentrations are predominantly smaller in the LIG-GHG-tr simulation than in the LIG-ctl-tr, the former simulation gives higher temperatures than the latter. The only difference between the two simulations, besides GHGs, is the vegetation. When used dynamically, the vegetation can lead to a cooling in the North Atlantic Ocean.

We have included also model-data comparison of LIG trends between 125 and 115 kyr BP from Capron et al. (2014) and from our COSMOS LIG-1300m-alb-tr and LIG-ctl-tr simulations, but because the main focus here are anomalies and due to the large amount of data, we have decided to include it in the Supplementary material. The comparison with the ice cores is provided in the text only, in order to limit the number of figures.

Comment:

3. My third comment relates in a more general way to the form of the paper: I find the manuscript long and unfortunately, too much information leads to the blurring of the main findings and makes it difficult to extract the most important results and their implication. I think that it originates from the three following reasons which should be fixed in the revised version:

Reply

We thank Emilie Capron for the suggestions. We have considered them in the revised version of the manuscript.

Comment:

- Some sections have excessive details, in particular in the Results and Discussion Sections. Specific paragraphs are highlighted and suggestions to shorten the text are given in the Specific comment" section of this review. I think the authors should keep this comment in mind for the whole manuscript when preparing the revised version.

Reply

We have removed some of the details and simplified the story and the text in the Results and Discussion sections of the revised manuscript.

Comment:

- It is also related to my first main concern related to the number of simulation outputs presented. I think that not all simulations and shown model outputs should necessarily be kept or if the authors really think they are all necessary, then, a strong effort of synthesis needs to be done.

Reply

As mentioned above, we have removed some of the simulations that do not relate to the main topic (GI and HOL-x0.5). We have also reduced the part of the paper that covers the evolution of temperature during the LIG and moved the figures with middle and low latitude temperature evolution to the Supplementary material. Since we use the transient simulations for calculation of the maximum and minimum LIG TS, we have kept the figure with the northern high-latitudes temperatures as an example figure, in order to give the reader a feeling on how these transient changes in temperature look like.

Comment:

- The manuscript is also long because of some redundant information in some sections (e.g. introduction and discussion). I indicate them in the "specific comment" section. Overall, the revised manuscript should be written in a more concise way.

Reply

We have aimed in the revised manuscript to write the story in a more concise way and remove redundant information.

I detail below specific remarks mostly related to my comments above and also some technical corrections that should be taken into account when preparing the revised version.

2. Specific comments:

Abstract:

Comment:

It needs to be re-written to clarify the main results of the study and make it more to the point. In particular, the authors should better highlight what new insights are provided by their study. In its current form, some information remains vague and sometimes unclear. Some of their conclusions are also similar to previous studies (e.g. problem of proxy seasonality, and chronology issues of the paleo-data). This is absolutely fine, however, they should try and better highlight why this is still of interest in the context of their new simulations (e.g. the fact that for the first time the height and the extent of Greenland is tested) and which results are specific to their work.

Reply

We have rewritten the abstract as suggested.

Comment:

P934, line 12: The sentence starting with "Reducing...." needs to be more specific. For instance : "...reducing the height by XX m...". Similar comment for "....leads to a warming of several degrees": Please, provide at least a temperature interval.

Reply

We have rephrased to "Reducing the height by ~1300 m and the extent of the GIS leads to a warming of up to +5°C [...]".

Comment:

P934, line 17: "with respect to the pattern". When reading the abstract, the reader may wonder if the authors mean a temporal pattern or a spatial pattern or both. Please, reformulate.

Reply

We have added "warming pattern".

Introduction:

Comment:

P936, line 13: this paragraph should be written in a more concise way. Although the sentence starting line 21 is slightly more specific, it is redundant with the sentence starting line 15.

Reply

We have rephrased part of this paragraph.

Comment:

P937, line 3: reformulate this sentence to : “Existing studies on the effects of a reduced GIS during the LIG have been centred mostly on the Northern Hemisphere and focused on implications related to sea level rise (Stone et al. 2013) and Atlantic Meridionnal overturning circulation (AMOC) (Bakker et al. 2012)”.

Reply

We have replaced the sentence as suggested.

Comment:

Also, please, don’t repeat twice the Bakker et al. (2012) and Stone et al. (2013) in the same sentence. In the same paragraph, two sentences later, the authors mention again these two studies. I think this paragraph could be shortened and still provide the same amount of information.

Reply

We have shortened this paragraph and wrote it in a more concise way.

Comment:

In this paragraph the authors should also add references to Loutre et al. (2014) who present some transient simulations for the LIG with an EMIC, as well as the study by Bakker and Rensen (2014) discussing the possible bias linked to the synchronicity hypothesis and that is cited later in the discussion in the current manuscript.

Reply

We have added these two references in the paragraph.

Comment:

P938, line 12 to line 18: Please, shorten the text to avoid redundancies.

Reply

We have rephrased and reorganized this part of the paragraph.

Comment:

P937, line 25: Papers by Capron et al. 2014 and Govin et al. 2012 discuss these issues more extensively.

Reply

We have added these references.

Comment:

P937, line 25: “On cause of the model-data...". This paragraph needs to be reformulated as the model-data is firstly related to the fact that the LIG synthesis the authors refer to represent one single snapshot on the LIG maximum warmth, and thus they imply that maximum warmth occur synchronously across the globe. Once the authors have said this, they should add a sentence explaining that the reason of such an approximation is linked to the difficulty to combine time series from different types of paleoclimatic archives since they do not benefit from robust absolute timescale allowing precise temporal comparison between regions and between archives. This issue is widely discussed by Capron et al. (2014).

Reply

We have reformulated and added the information as suggested.

Section 2: Data and Methods

Comment:

P940, line 12: What is the specific interest to focus on the CH_4 effect rather than the CO_2 effect? I am not sure that the simulation testing the effect of CH_4 is particularly necessary and it doesn’t seem to me that the effect of methane on climate is very much discussed later on. The authors should consider removing it.

Reply

We have provided the explanation for using higher CH_4 concentrations in the reply of the first main comment. The changes in GHGs are not the main interest in this study, but since it was necessary to include a simulation with increased methane concentrations, we also looked at those results. However, in order to shorten the story, the figure with the effect of an increased atmospheric methane concentration on the TS is removed from the Supplementary material of the revised manuscript.

Comment:

P940, line 13: The simulation with GHG prescribed such as LIG-PMIP is an important simulation and very appropriate for comparison with existing simulations that also follow PMIP recommendations. That's why the authors use it in the discussion. Thus I don't understand why it appears in the Supplementary Material.

Reply

The simulation with GHG concentrations as suggested by PMIP3 protocol (LIG-GHG) is actually not of particular relevance to the main topic of this study. We have included this simulation in the Supplementary material (now Fig. S1 in the revised version) in order to show how large is the impact of lower GHG concentrations compared to concentrations used in our LIG sensitivity simulations. We only want to show that there is not a large difference between using relatively lower and larger values when simulating the 130 kyr BP time slice. Thus, assuming linearity, the results of the LIG simulations with reduced GIS should be similar even when GHG concentrations as proposed by PMIP3 would be used. One has to take into account also that in Fig. S1 we see not only the effect of lower GHG concentrations but also of the vegetation, which in case of the LIG-GHG is fixed to PI, while in the LIG-ctl is computed dynamically.

Comment:

P941, line 13: The authors perform statistical tests to evaluate the significance of their results. Those tests highlight variations from one simulated parameter to the other in the total area that can be/cannot be interpreted and also in the geographical regions: My question might be naive but where does this come from? Why the significance of the results varies from one simulation from the others? this may deserve to be shortly discussed somewhere in the revised manuscript.

Reply

The statistical significance t-test between two simulations vary according to how large the anomalies are. The larger the anomaly the more likely it is significant.

Section 3: Results

Comment:

Some descriptions need to be removed in this section. At the moment, it is too long and I think it is easy to get lost into the details.

Reply

This section is shortened in the revised manuscript.

Comment:

Section 3.1: One way to shorten this section would be to present global SAT, Northern Hemisphere SAT, Southern Hemiphere SAT with annual, winter average etc... for the different simulations, in a Table to avoid the long text. In the text, the authors could only highlight the most relevant patterns and refer to the Table.

Reply

We have removed the detailed description of the TS averages, but we do not consider an extra table necessary since the absolute values of the global, Northern Hemisphere, and Southern Hemisphere TS averages in all equilibrium simulations calculated for annual, summer, and winter mean are given in Table 2 and the differences can be calculated from there. Instead, we focus now in the text only on the main pattern and differences between the simulations with reduced GIS.

Comment:

Section 3.2 needs to be shortened too and again with a focus on the important patterns for some specific key regions. However, I think the authors should highlight more clearly here that their simulations show that the timing of the maximum warmth is different between the winter signals and the summer signals (as seen in Figure 6).

Reply

We have also shortened this section, especially that we have moved to the Supplementary material, the figures with averages of middle and low latitudes TS evolution. We have also highlighted the differences in the timing of the maximum warmth between summer and winter.

Comment:

Section 3.3: This section is too long and need to be shortened as well.

Reply

This section is also shortened and more synthesized in the revised manuscript.

Section 4: Discussion

Comment:

This section should be shortened and should proposed more synthesized and critical discussions.

Reply

In the revised version we aim for a more synthesized and critical discussion.

Comment:

Section 4.1: In its current form, I don't think this discussion is very useful. I don't identify what is new relative to previous studies. It would benefit from being a bit more quantitative in the following sentence:

P956,line 22: "...a global warming of up to XX°C in our LIG simulations...." If the purpose of the study is to quantify the possible contribution of reduced GIS elevation in combination with insolation forcing, I would have expected a discussion on the relative effect of the insolation versus the effect of the reduced GIS elevation.

Reply

We have added the exact contribution of insolation to global annual mean warming. However, since the focus is the contribution of GIS changes to the LIG climate, we have rephrased the first sentence of the Dicussion section for more clarity and we focus more on a discussion on the changes in GIS rather than insolation. We additionally give an overview on which forcing is dominant globally and in the hemispheres during summer and winter seasons and annual mean.

Comment:

Section 4.2: This section is too long. On one side, it should be shortened and less descriptive: the first paragraphs of the section are somehow a presentation of results again. But I think also that on the other side, results should be discussed more in the context of previous studies. At the end of this section, the authors should emphasize better, the outcomes specific to their study about the influence of Greenland Ice Sheet elevation on surface air temperature during the LIG.

Reply

This section is also shortened in the revised version of the manuscript and we have tried to avoid redundancies and to clarify the main message of this study. A discussion in the context of previous studies is also included.

Comment:

Section 4.3: The results should be also discussed in relation with the recent transient climate simulations for the LIG performed by Loutre et al. 2014 using the LOVECLIM model.

Reply

The study by Loutre et al. (2014) is now included in the discussion of the revised manuscript.

Comment:

Section 4.4: Section is too long and needs to be synthesized a lot. The authors should also better highlight what their study provided compared to the previous simulations of Otto-Bliesner et al. (2006, 2013) and Lunt et al. (2013).

Reply

This section is also shortened and better organized in the new manuscript version.

Comment:

Section 4.5: The ideas developed in this section need to be re-organized.

P966, line 10: the issue of dating paleoclimate archives should be the first thing to write as this is the reason why defining the timing of the maximum warmth of the LIG is so hard to define and why it results in data synthesis that perform some temperature averaging procedure and produce only one snapshot on the data synthesis. The authors should discuss their results with the recent data synthesis by Capron et al. (2014).

Reply

We have re-organized the section as suggested.

Conclusion

Comment:

The conclusion should be more concise but should more clearly state the implication of the study. For instance, in the end, is it possible to tell the simulation that seems to be the most appropriate to explain the data (Which extent? which height for the Greenland Ice sheet?). A couple of sentences about more specific perspectives for future work should also be presented.

Reply

We have re-organized the Conclusions section as well. A reduction in GIS improves the model-data comparison if annual mean proxies are used, since the GIS changes strongly influence winter season rather than summer, therefore when summer proxies are used a reduction in GIS does not reduce the dissagreement.

3. Stylistic and typographic comments

P934.

Comment:

- Abstract: Add a sentence of perspectives at the end.

Reply

We have added.

Comment:

- line 1: “(LIG, ~130-115 kiloyear before present)”. Please add the “approximative” sign as these numbers can vary slightly from one paper to the other depending on how the LIG is defined. For instance, in the IPCC AR5, it is defined based on the sea level variations from and is given as 129-115 ka (Dutton and Lambeck, 2012; Masson-Delmotte et al., 2013).

Reply

We have added the “approximative” sign.

Comment:

- line 8: to assess

Reply

Done.

Comment:

- line 10: “whole LIG and Holocene”: for each one, please give the exact intervals for which the transient simulations have been run, i.e. 130-115ka and 8-0 ka.

Reply

Done

Comment:

- line 13: “leads to an ADDITIONNAL warming...”

Reply

Done.

Comment:

- line 24: instead of writing "deficits", the authors should be more specific and evoke that there are likely still some remaining processes that are missing in the model (and cite a couple ?).

Reply

Done.

P935.

Comment:

- line 26: see previous comment for line 1, P934.

Reply

Done.

Comment:

-line 18: add the Turney and Jones (2010) paper in the list of reference.

Reply

Done.

Comment:

-line 23: the sentence "Proxy records..." and the sentence line 18 starting with "The Last Interglacial..." should be combined as they convey a similar message with the the sentence starting line 23 being more specific.

Reply

The idea behind the order of these sentences was to first state that the LIG was in general considered warmer than PI and then continue with model and reconstruction studies on the LIG warmth. If we would combine those two sentences, we think it would create confusion, especially with respect to the references.

P936.

Comment:

- line 18: "....ice core data proposes only a modest change, I.E. EQUIVALENT TO A CONTRIBUTION IN SEA LEVEL OF ABOUT 2 m".

Reply

Done.

Comment:

- line 13: this paragraph should be written in a more concise way. Sentences starting line 15 and line 21 are repetitive with again the sentence from line 21 being more specific.

Reply

We have rephrased parts of this paragraph.

P937.

Comment:

-line 7: "...to a pronounced warming OF ABOUT XX"..." please, provide a quantitative estimate.

Reply

Done.

Comment:

-line 24: Please reformulate the sentence such as: " The lack of accurate and independent age models for most paleoclimatic record during the LIG could be one cause for the observed model-data discrepancy".

Reply

Done.

P938.

Comment:

-line 14: "....of transient simulations of the entire LIG (GIVE TIME INTERVAL)".

Reply

We have removed this part from the sentence after rephrasing the paragraph for clarity.

P940.

Comment:

The authors should indicate clearly in the experimental setup section the time slices that are performed (mid-holocene, 130, 125 and 115 ka, etc...)

Reply

Done.

Along those lines:

Comment:

-line 5: Please reformulate " 3 equilibrium simulations covering the LIG are performed, using fixed boundary conditions for the 130 ka, 125 ka and 115 ka time slices".

Reply

We have reformulated as suggested without the 115 kyr BP time slice since this is removed in the revised version.

Comment:

-line 13: please reformulate : "An additional simulation is performed using VALUES for GHG concentrations proposed in the ....(PMIP3) FOR THE TIME INTERVAL XX ka (E.G. LUNT ET AL. 2012) AND CORRESPONDING TO 257ppm for CO_2, 512ppm for CH_4 and 239ppbv for N_2O.....at 130 ka".

Reply

Done.

P944.

Comment:

-line 4: replace chapter by section.

Reply

Done.

Comment:

-line 7: it would be good to be consistent with the amount of digits given when providing quantitative estimate of SAT for instance, at the moment: "+11.1°C", "~2°C", +0.36°C"...

Reply

We agree that is is important be consistent. However, when we give approximations like "~2°C", we do not think is necessary to add digits. Similarly, when giving estimates like "up to +11.1°C" it depends on the case. In results from our study, we are able to provide one digit but not for estimates taken from other studies. We give the two digits when we calculate temperature averages or trends because in some cases the differences in the TS of different simulations are rather small.

Comment:

- line 16: "...LIG-x0.5 RELATIVE TO LIG-CTRL."

Reply

Done.

P945.

Comment:

line 4: "...the Sea of Okhotsk (WESTERN PACIFIC OCEAN)"

Reply

Done.

P959.

Comment:

-lines 9 to 15. Please be more concise. This is not necessary to describe again all this. The justification of the latitudinal band should not appear in the discussion section.

Reply

Done.

P968.

Comment:

-line 14. Please reformulate the first sentence to : "....general circulation model AND ASSESS THE INFLUENCE OF THE GIS ON GLOBAL CLIMATE. And "we employed..."sentence can be removed.

Reply

Done.

Comment:

-line 19. Please be more specific and add an example: “a reduced GIS of XX m”, “ the warming by YY°C”,

Reply

Done.

4. Tables and figures

Comment:

Figure 2.

- I suggest to remove here and in the rest of the captions for other figures the expression “...at the beginning of the LIG (130ka) and replace it simply by “...in the 130 ka simulation.”

Reply

Done.

Comment:

Figure 3.

-Please reformulate first sentence such as: “Effect of Greenland Ice Sheet elevation and albedo on SAT at 130 kyr BP”.

Reply

Done.

Comment:

Figure 4.

-the violet dashed line is hard to see.

Reply

We have changed the colorbar of all maps in order to distinguish easier between different shades. The violet dashed lines are therefore now easier to see. Furthermore, we could not find a better visible color.

Comment:

Figure 8.

I am not convinced that the values of RSMD should appear in the caption of the figure. Please consider providing a comparison with the recent 130 ka data time slice produced by Capron et al. (2014).

Reply

We have removed the RMSD values from the figure captions and created three tables in the Supplementary material of the revised manuscript, one table for each dataset: CAPE Last Interglacial Project Members (2006), Turney and Jones (2010), and Capron et al. (2014).

5. References

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Abstract

During the Last Interglacial (LIG, ~130–115 kiloyear (kyr) before present (BP)), the northern high latitudes were characterized by~~experienced~~ higher temperatures than those of the late Holocene ~~with a notably~~and a lower Greenland Ice Sheet (GIS). However, the impact of a reduced GIS on the global climate has not yet been well constrained. In this study, we quantify the contribution of the GIS to LIG warmth by performing various sensitivity studies based on equilibrium simulations, employing the Community Earth System Models (COSMOS), with a focus on height and extent of the GIS. We present the first study on the effects of a reduction in GIS on the global surface temperature (TS) anomalies and separate the contribution of different forcings to LIG warmth. The strong Northern Hemisphere warming is mainly caused by increased summer insolation. Reducing the height by ~1300 m and the extent of the GIS does not have a strong influence during summer, leading to an additional warming of only +0.24°C. The effect of a reduction in GIS is strongest during local winter, with up to +5°C warming in the northern and southern high latitudes and an increase in global average temperature of +0.48°C. Furthermore, the method by which GIS configuration is changed influences the results. ~~In order to asses the effects of insolation changes over time and for a comparison of LIG climate with the current interglacial, we perform transient simulations covering the whole LIG and Holocene. We analyze surface air temperature (SAT) and separate the contribution of different forcings to LIG warmth. The strong Northern Hemisphere warming is mainly caused by increased summer insolation. Reducing the height and extent of the GIS leads to a warming of several degrees Celcius in the northern and southern high latitudes during local winter.~~

In order to evaluate the performance of our LIG simulations, we additionally compare the simulated ~~SAT~~TS anomalies with marine and terrestrial proxy-based LIG temperature anomalies derived from three different proxy data compilations. Our model results are in good agreement with proxy records with respect to the warming pattern, but underestimate the reconstructed temperatures, suggesting a potential misinterpretation of the proxy records or deficits of our model such as low resolution, lack of biogeochemistry feedback, of lithosphere, or of a coupled ice sheet model).. However, ~~W~~we are able to partly reduce the mismatch between model and data by additionally taking into account the potential seasonal bias of the proxy record and the uncertainties in the dating of the proxy records for the LIG thermal maximum. The seasonal bias and the uncertainty of the timing are estimated from our own transient model simulations covering the whole LIG (130–115 kyr BP). ~~We note however that our LIG simulations are not able to reproduce the full magnitude of temperature changes indicated by the~~

~~proxies, suggesting a potential misinterpretation of the proxy records or deficits of our model.~~ Changes in GIS improve the model-data agreement when annual mean proxies are considered rather proxies that record summer temperatures. Additionally, by comparing our model results to temperature reconstructions we can conclude that the GIS elevation was not as low as prescribed in our simulations, but potentially lower than prescribed in other studies. Thus, the question regarding the real size of the GIS during the LIG has yet to be answered.

1. Introduction

One important application of atmosphere–ocean general circulation models (AOGCMs) is the ~~projections~~computation of future climate projections (Collins et al., 2013; Kirtman et al., 2013). These projections allow insight into possible future climate states that may be notably different from present day. In order to ensure the reliability of such climate projections, the climate models' ability to replicate climate states that are different from the present ~~(e.g. Braconnot et al., 2012; Flato et al., 2013)~~ needs to be tested (e.g. Braconnot et al., 2012; Flato et al., 2013) – this is necessary since model development is biased towards present climate states as a result of the tuning of various physical parameterizations towards modern observations. Past ~~geologic timescales~~time periods provide the means for evaluating the performance of general circulation models ~~are a useful test bed for this purpose~~(e.g. Dowsett et al., 2013; Lohmann et al., 2013; Lunt et al., 2013).

In particular, the simulation of interglacial climates provides an example of how models can respond when strong changes in the forcing are applied (Mearns et al., 2001). ~~Analyzing the main drivers that cause an interglacial climate that is warmer than the current interglacial, the Holocene, can help us to better understand and assess potential future climate change.~~For a better understanding and assessment of potential future climate change it is necessary to analyze the main drivers leading to an interglacial climate that was warmer than the present interglacial. The Last Interglacial (LIG, ~130–115 kiloyear (kyr) before present (BP)) represents the penultimate interglacial before the Holocene (10–0 kyr BP), and~~. The LIG~~ is considered to be on average warmer than the Holocene (CLIMAP Project Members, 1984; Martinson et al., 1987; Kukla et al., 2002; Bauch and Erlenkeuser, 2003; Felis et al., 2004; Kaspar et al., 2005; Jansen et al., 2007; Turney and Jones, 2010; Masson-Delmotte et al., 2013). Model simulations indicate a pronounced warming during boreal summer in northern high latitudes (Harrison et al., 1995; Kaspar et al., 2005; Otto-Bliesner et al., 2006; Lohmann and Lorenz, 2007; Stone et al., 2013). Proxy records located in the Northern Hemisphere ~~(NH)~~ indicate also that LIG climate is characterized by temperatures that are several degrees Celsius above preindustrial (PI) values

(Kaspar et al., 2005; CAPE Last Interglacial Project Members, 2006; Turney and Jones, 2010; Mckay et al., 2011). According to climate reconstructions, Arctic summer temperatures were about +2 to +4°C warmer than those of the late Holocene (CAPE Last Interglacial Project Members, 2006). Winter in high latitudes is also considered to be warmer during the LIG due to sea ice feedbacks (Montoya et al., 2000; Kaspar et al., 2005; Yin and Berger, 2010). One cause for LIG warmth in summer was increased summer insolation at middle to high latitudes at the expense of winter insolation in the tropics. Enhanced seasonality in the NHNorthern Hemisphere is attributed to larger obliquity (ε) and eccentricity (e) relative to today (Berger, 1978), with Earth's orbital eccentricity being more than twice the PI value (Berger and Loutre, 1991), and boreal summer coinciding with the Earth passing the perihelion (Laskar et al., 2004; Yin and Berger, 2010). Greenhouse gas (GHG) concentrations during the LIG were similar to PI. Changes in the insolation forcing determine feedbacks in the ocean, atmosphere, vegetation, and sea ice, which further influence the climate (e.g. Berger and Loutre, 1991; Braconnot et al., 2012).

According to different studies, Tthe Greenland Ice Sheet (GIS) is considered to bewas lower during the LIG as compared to PI, but the magnitude of reduction of elevation and area of the GIS has yet to be determined. Some studies based on reconstructions and climate model simulations suggest a partial or complete absence of the GIS during the LIG, and that the sea level was higher than PI (Veeh, 1966; Stirling et al., 1998; Cuffey and Marshall, 2000; Otto-Bliesner et al., 2006; Overpeck et al., 2006; Jansen et al., 2007; Kopp et al., 2009, 2013; Alley et al., 2010; van de Berg et al., 2011; Robinson et al., 2011; Dutton and Lambeck, 2012; Dahl-Jensen et al., 2013; Quiquet et al., 2013; Church et al., 2013; Stone et al., 2013), while a more recent study based on ice core data proposes only a modest GIS change (i.e. equivalent to a contribution to sea level rise of ~2 m, Dahl-Jensen et al., 2013). If the LIG is indeed characterized by a pronounced loss of ice volume over Greenland, then the global sea level was likely higher than today – a scenario that also has been suggested for the climate of the future (Rahmstorf, 2007; Church et al., 2013). An increase in sea level during the LIG as high as 8 m is proposed by Kopp et al. (2009) based on sea level data synthesis, which may imply a large contribution from the GIS and the Antarctic Ice Sheet. The contribution of a partially melted GIS to LIG sea level rise is not yet well determined; proxy records and models various studies suggest that there is a contribution of a partially melted GIS to sea level rise, but the magnitude is subject to debatea sea level rise due to meltwater from Greenland of +0.3 to +5.5 m (Veeh, 1966; Stirling et al., 1998;Cuffey and Marshall, 2000; Tarasov and Peltier, 2003; Lhomme et al., 2005; Otto-Bliesner et al., 2006; Overpeck et al., 2006; Jansen et al., 2007; Kopp et al., 2009, 2013; Dutton and Lambeck, 2012; Dahl-Jensen et al., 2013; Colville et al., 2011; Quiquet et al., 2013; Church et al., 2013; Stone et al., 2013). An increase in sea level during the LIG as high as 8 m is proposed by Kopp et al. (2009) based on sea level data synthesis, which may imply a large contribution from the GIS and the Antarctic Ice Sheet. Otto-Bliesner et al. (2006) and Stone et al. (2013) suggest that the GIS contributed to a sea level change of +0.3 to +3.6 m during the LIG.

Existing studies on the effects of a reduced GIS during the LIG have been centered mostly on the Northern Hemisphere and focused on implications related to sea level rise (Stone et al. 2013) and Atlantic Meridional Overturning Circulation (AMOC) (Bakker et al. 2012).There are studies on the effects of a reduced GIS during the LIG, but for the NH (Otto-Bliesner et al., 2006; Bakker et al., 2012; Pfeiffer and Lohmann, 2013; Stone et al., 2013) and with a focus on sea level rise (Stone et al., 2013) and Atlantic meridional overturning circulation (AMOC) (Bakker et al., 2012). The studies by Bakker et al. (2012) and Stone et al. (2013) assume a relatively modest reduction of the GIS but find a mismatch between the simulated and the proxy-based temperature anomalies with respect to PI (CAPE Last Interglacial Project Members, 2006). Otto-Bliesner et al. (2006) find that a GIS elevation reduced by 500 m leads to a pronounced warming of up to +5°C in the middle to high latitude summer. However, when comparing to marine and terrestrial proxy-based temperature anomalies with respect to PI (CAPE Last Interglacial Project Members, 2006) they find as well a mismatch between model and data, with the model underestimating the temperature anomaly indicated by the proxy record. Two studies assume a relatively modest reduction of the GIS (Bakker et al., 2012; Stone et al., 2013) and find as well a mismatch between the modelled and the proxy-based temperature anomalies (CAPE Last Interglacial Project Members, 2006). In an LIG study based on transient climate model simulations performed with an earth system model of intermediate complexity, Loutre et al. (2014) find that changes in the Northern Hemisphere ice sheets configuration (extent and albedo) have only a small impact on the climate at the beginning of the LIG. They find as well an underestimation of the reconstructed temperatures by the model, even when taking into account several uncertainties. Bakker and Renssen (2014), who perform an analysis of transient simulations for the LIG, provide a partial explanation for the model-data mismatch, proposing that such large differences between the reconstructed and simulated LIG temperatures may stem from the assumption in temperatures reconstructions that the LIG thermal maximum occurred synchronously in space and time. Their study suggests that global compilations of reconstructed LIG thermal maximum overestimate the warming.

Another model-data comparison study (Otto-Bliesner et al., 2013) for the LIG, based on an AOGCM (but with no changes in GIS elevation or extent) also shows an underestimation of global temperature reconstructions by Turney and Jones (2010) and McKay et al. (2011). Lunt et al. (2013) compare global terrestrial and marine proxy-based temperature anomalies with respect to PI by Turney and Jones (2010) to an ensemble of equilibrium simulations for the LIG performed with different state-of-the-art climate models. Even when considering a multi-model and a multi-proxy approach, they also find a pronounced disagreement between model and data, with the model underestimating the reconstructed temperature.

~~One cause for the model-data discrepancy may be related to uncertainties in absolute dating of marine proxy records~~The lack of accurate and independent age models for most paleoclimatic record during the LIG could be one cause for the observed model-data discrepancy (e.g. Drysdale et al., 2009; Govin et al., 2012; Capron et al., 2014)~~, as there is no straightforward dating method available~~. For example, the compilation of LIG temperature reconstructions included in this study (CAPE Last Interglacial Project Members, 2006) represents one single snapshot on the LIG thermal maximum, with the assumption that maximum warmth occurred synchronously across the globe. This assumption has to be made when compiling reconstructed LIG temperatures as it is difficult to align time series from different types of paleoclimatic archives since they do not benefit from robust absolute timescale allowing precise temporal comparison between regions and between archives (Capron et al., 2014).

Moreover, different studies (modelling as well as proxy-based) indicate that the maximum LIG warmth occurred at different times throughout the LIG in dependence of the geographical location (Bakker et al., 2012; Govin et al., 2012; Langebroek and Nisancioglu, 2014). Additionally, some proxy records may be seasonally biased (Lohmann et al., 2013, and references therein). Still, the models used by Lunt et al. (2013) and Otto-Bliesner et al. (2013) do not capture the magnitude of change recorded by the proxies, even when ~~modelled~~simulated summer mean temperature anomalies are considered.

Transient LIG climate simulations provide the possibility to determine when and where maximum LIG warmth occurred, and whether a given record may be seasonally biased or rather represents annual mean temperatures. Therefore, transient climate simulations may help to clarify the origin of the disagreement between model and data.~~In our study, we present an analysis of global climate of a warmer-than-present interglacial. We discuss results from AOGCM simulations of the beginning of the LIG (130 kyr BP) and of transient simulations of the entire LIG. In model sensitivity studies, we assume a strong change of GIS height and reduce it to half its present value. We analyze the impact of~~

~~such a change in boundary conditions on the global climate with a focus on surface air temperature (SAT). We investigate the relative effect of three physical characteristics on LIG warmth: astronomical forcing, reduced elevation and extent of the GIS, and the resulting albedo changes. This approach enables us to quantify the effect of a reduced GIS on global SATs and to assess the importance of additional forcings like insolation and albedo. Furthermore, in order to validate the performance of the utilized climate model and to explore whether a reduced GIS may indeed have played an important role for LIG warmth, we perform a model-data comparison using data compilations for the NH~~

~~(CAPE Last Interglacial Project Members, 2006) and for the entire globe (Turney and Jones, 2010). Moreover, all the LIG simulations used in other model-data comparison studies assumed one of the following settings: no change in the GIS, only a modest reduction, or a complete deglaciation.~~In this study, we analyze the effect of a reduced GIS on LIG global climate with a focus on surface temperature (TS) at 130 kyr BP. The TS is derived from equilibrium simulations performed with the AOGCM COSMOS. We perform several sensitivity simulations with different boundary conditions and use three different methods of reducing GIS elevation to half its preindustrial elevation and/or extent. This approach enables us to determine what GIS configuration has the strongest impact on the global temperature. Additionally, we assess the importance of additional forcings like insolation and albedo. Furthermore, in order to validate our results, we perform a model-data comparison using three different proxy-based temperature compilations by CAPE Last Interglacial Project Members (2006), Turney and Jones (2010), and Capron et al. (2014). For model-data comparison, we additionally consider the timing uncertainty of the maximum LIG warmth as determined from our transient simulations as well as the potential seasonal bias of the proxy record.

2. Data and methods

2.1 Model description

The Community Earth System Models (COSMOS) consist of the general atmosphere circulation model ECHAM5 (5th generation of the European Centre Hamburg Model; Roeckner et al., 2003), the land surface and vegetation model JSBACH (Jena Scheme of Atmosphere Coupling in Hamburg; Raddatz et al., 2007), the general ocean circulation model MPIOM (Max-Planck-Institute Ocean Model; Marsland et al., 2003), and the OASIS3 coupler (Ocean-Atmosphere-Sea Ice-Soil; Valcke et al., 2003; Valcke, 2013) that enables the atmosphere and ocean to interact with each other. COSMOS is mainly developed at the Max-Planck-Institute for Meteorology in Hamburg (Germany). The atmospheric component

ECHAM5 is a spectral model, which is used in this study at a horizontal resolution of T31 (~3.75°×3.75°) with a vertical resolution of 19 hybrid sigma-pressure levels, the highest level being located at 10 hPa. The JSBACH simulates fluxes of energy, momentum, and CO_2 between land and atmosphere and comprises the dynamic vegetation module by Brovkin et al. (2009) which enables the terrestrial plant cover to explicitly adjust to variations in the climate state. MPIOM is formulated on a bipolar orthogonal spherical coordinate system. We employ it at a horizontal resolution of GR30 (corresponding to ~3°×1.8°) with 40 vertical levels. MPIOM includes a Hibler-type zero-layer dynamic-thermodynamic sea ice model with viscous plastic rheology (Semtner, 1976; Hibler, 1979). No flux correction is applied (Jungclaus et al., 2006)~~, allowing for applications of the model for climate states beyond present~~. Model time steps are 40 min (atmosphere) and 144 min (ocean). This COSMOS configuration has been applied for the mid- and early Holocene (Wei and Lohmann, 2012), glacial conditions (Gong et al., 2013; Zhang et al., 2013, 2014), the Pliocene (Stepanek and Lohmann, 2012), the Miocene (Knorr et al., 2011; Knorr and Lohmann, 2014),~~ and~~ future climate projections (Gierz et al., 2015), and the LIG (Lunt et al., 2013; Pfeiffer and Lohmann, 2013; Bakker et al., 2014; Felis et al., 2015; Gong et al., 2015; Jennings et al., 2015).

2.2 Experimental setup

As control climate we use a PI simulation described by Wei et al. (2012). Greenhouse gas concentrations and astronomical forcing of the PI simulation are prescribed according to the Paleoclimate Modelling Intercomparison Project Phase 2 (PMIP2) protocol (Braconnot et al., 2007). Several~~The LIG~~ equilibrium simulations covering the LIG are performed using fixed boundary conditions for 130 and 125 kyr BP time slices. The latter simulation is performed in order to assess whether a reduction in GIS at 125 kyr BP improves the model-data agreement. Astronomical parameters for the time slices considered in this study have been calculated according to Berger (1978) and are given in Table 1. It is known that one main driver for LIG climate is the Earth's astronomical parameters (Kutzbach et al., 1991; Crowley and Kim, 1994; Montoya et al., 2000; Felis et al., 2004; Kaspar and Cubasch, 2007). During the early part of the LIG, the axial tilt (obliquity) was higher which caused stronger summer insolation at high latitudes of the Northern Hemisphere, while the low latitudes received less insolation; this effect manifests in enhanced seasonality (i.e. warmer summers and cooler winters) in the early LIG climate. The Earth's orbital eccentricity was more than twice the present-day value (Berger and Loutre, 1991), and boreal summer coincided with the Earth passing the perihelion (Laskar et al., 2004; Yin and Berger, 2010).

Our main focus is the effects of ~~astronomical forcing and~~ height and extent of the GIS and insolation changes on climate; consequently, GHG concentrations are prescribed at mid-Holocene levels (278 parts per million by volume (ppmv) CO_2, 650 parts per billion by volume 10 (ppbv) CH_4, and 270 ppbv N_2O, Table 1).~~ One simulation is forced with increased CH_4 (760 ppbv) in order to elaborate the effect of methane on climate (Table 1, Fig. S2)~~. An additional simulation is performed using ~~the~~values for GHG concentrations~~ as~~ proposed ~~by~~in the Paleoclimate Modelling Intercomparison Project Phase 3 (PMIP3) for the 130 kyr BP time slice (e.g. Lunt et al., 2012) ~~with values of~~and corresponding to 257 ppmv for CO_2, 512 ppbv for CH_4, and 239 ppbv for N_2O (LIG-GHG, Table 1, Fig. S~~5~~1). This simulation is included in the Supplementary material as a control run for the GHG concentrations used in our LIG sensitivity simulations, in order to show that there is no large scale impact of lower GHG concentrations relative to our LIG control simulation (Fig. S1). Another LIG simulation is forced with increased CH_4 (760 ppbv) and slightly increased CO_2 (280 ppmv) in order to have one LIG simulation that has identical GHG concentrations as the ones prescribed in the PI simulation (Wei et al., 2012) (Table 1).

The size of the GIS during the LIG is not well constrained by reconstructions (Koerner, 1989; Koerner and Fisher, 2002; NGRIP members, 2004; Johnsen and Vinther, 2007; Willerslev et al., 2007; Alley et al., 2010; Dahl-Jensen et al., 2013). We take this uncertainty into account and perform sensitivity simulations with three different elevations and two different ice sheet areas of the GIS (Fig. 1). An LIG simulation (LIG-ctl) with a preindustrial~~sent~~ GIS elevation (Table 1, Fig. 1a) is used as control run for our LIG simulations, which allows us to quantify the exclusive effects of Greenland elevation on climate. Four simulations (Table 1) are performed using a modified GIS. We consider (1) a GIS lowered to half its present elevation (LIG-×0.5) with unchanged GIS area (Fig. 1b); (2) a GIS lowered by 1300 m (LIG-1300-m); at locations where the ~~PI~~preindustrial Greenland elevation is below 1300 m, we set LIG orography to zero meters, but define the ground to be ice covered and keep the albedo at values typical for the GIS (Fig. 1c); (3) a GIS similar to simulation LIG-1300-m, but with albedo adjustment at locations where prescribed LIG orography is zero meters (LIG-1300-m-alb); at such locations the land surface is defined as being ice-free and the background albedo is reduced from 0.7 to 0.16 (Fig. 1d), an albedo value that is typical for tundra (Fitzjarrald and Moore, 1992; Eugster et al., 2000) – this simulation, in combination with simulations LIG-1300-m and LIG-ctl, allows us to separate the climatic effects of a lowered and spatially reduced GIS from those of changes in albedo; (4) a simulation similar to (3), but with an atmospheric concentration of CH_4 that is increased to 760 ppbv (LIG-1300-m-alb-CH_4, Fig. 1d); this simulation enables us to quantify the combined effect of a lowered GIS elevation, changes in albedo and insolation with respect to PI~~the separation of the climatic effects of a higher PI CH_4 (with respect to LIG concentration) as it was prescribed by the PMIP2 protocol~~.

Such changes in GIS elevation and extent would lead to a sea level rise of about 3 m instead of 7 m for the present situation due to the rebound effect (relaxation of the lithosphere). A sea level change of +3 m is in agreement with other studies that suggest an increase in sea level of 0.3 to 5.5 m during the LIG as a result of GIS melting (Cuffey and Marshall, 2000; Tarasov and Peltier, 2003; Lhomme et al., 2005; Otto-Bliesner et al., 2006; Carlson et al., 2008; Colville et al., 2011; Quiquet et al., 2013; Stone et al., 2013). Generally, other boundary conditions of the simulations are kept at their preindustrial~~PI~~ state, except for vegetation which is computed dynamically according to the prevailing climate conditions (the only equilibrium simulation that~~LIG-GHG~~ considers fixed ~~PI~~preindustrial vegetation is LIG-GHG).

Furthermore, we perform one transient model simulation that covers the Holocene (8–0 kyr BP) and four transient simulations of the LIG (130–115 kyr BP). The Holocene transient simulation is included in this study as a control run for the LIG transient simulations, in order to assess the differences and similarities between the present and last interglacial. For the LIG, we apply orography configurations of simulations LIG-ctl, LIG-×0.5, LIG-1300m-alb, and LIG-GHG, respectively. These LIG transient simulations enable us to extract the temperatures at the LIG thermal maximum. The transient simulations are started from a near-equilibrium state, meaning that the climate system is already adjusted to the prescribed forcings, except for the ocean which needs about 3000 years in order to reach an equilibrium state. Performing such long equilibrium simulations is not feasible due to the involved computational effort. Each transient simulation is accelerated by a factor of ten in order to reduce the computational expense. To this end, astronomical forcing is accelerated following the method of Lorenz and Lohmann (2004). The astronomical parameters are calculated after Berger (1978). During the simulations, the trace gas concentrations remain fixed – except for the LIG-GHG-tr run, where a timeseries is prescribed according to Lüthi et al. (2008) for CO_2, Loulergue et al. (2008) for CH_4, and Spahni et al. (2005) for N_2O, as proposed for PMIP3. The respective values are interpolated to a 0.01 kyr resolution that corresponds to the accelerated model time axis. A fixed preindustrial vegetation is considered only in the LIG-GHG-tr simulation, in the other transient simulations vegetation is computed dynamically. For the Holocene run, the orography is identical to preindustrial conditions.

In order to determine whether ~~SAT~~TS anomalies between simulations are statistically significant or rather caused by internal variability (noise), we perform an independent two-tailed Student's t test t following Eq. (1). For each grid cell, it relates time averages X and standard deviations σ of model output time series of two given model simulations X_1 and X_2 of a length of n timesteps, in dependence of the effective degrees of freedom (DOF_{eff}). The DOF_{eff} are calculated considering the lag-1 autocorrelation acf (von Storch and Zwiers, 1999):

$$DOF_{eff} = n(1-\mathrm{acf})/(1+\mathrm{acf}) \quad \text{with} \quad \mathrm{acf} = \max(\mathrm{acf}, 0),$$

meaning that the DOF_{eff} cannot be higher than 50, as the last 50 model years of each simulation are used for the analysis. For each grid point from X_1 and X_2 simulations, the smaller DOF_{eff} value is used for calculating the significance value with a 95% confidence interval.

$$t = \frac{\overline{X_1} - \overline{X_2}}{\sqrt{\frac{\sigma^2(X_1)}{n} + \frac{\sigma^2(X_2)}{n}}} \qquad (1)$$

Surface~~ air~~ temperature at locations where the t test t of two data sets indicates a significance value below the critical value is considered to be statistically insignificant and is marked by hatches on geographical maps presented throughout this study.

~~Furthermore, we perform one transient model simulation that covers the Holocene (8–0 kyr BP) and four transient simulations of the LIG (130–115 kyr BP). For the latter, we apply orography configurations of simulations LIG-ctl, LIG-×0.5, LIG-1300 m-alb, and LIG-GHG, respectively. The transient simulations are started from a near-equilibrium state. Each transient simulation is accelerated by a factor of ten in order to reduce the computational expense. To this end, astronomical forcing is accelerated following the method of Lorenz and Lohmann (2004). The astronomical parameters are calculated after Berger (1978). During the simulations, the trace gas concentrations remain fixed – except for the LIG-GHG-tr run, where a timeseries is prescribed according to Lüthi et al. (2008) for CO_2, Loulergue et al. (2008) for CH_4, and Spahni et al. (2005) for N_2O, as proposed for PMIP3. The respective values are interpolated to a 0.01 kyr resolution that corresponds to the accelerated model time axis. A fixed PI vegetation is considered only in the LIG-GHG-tr simulation, in the other simulations vegetation is computed dynamically. For the Holocene run, the orography is identical to PI conditions.~~

For the analysis of time slice simulations, we define winter and summer as the mean of the 50 coldest and warmest months, respectively, for each grid cell, as we are mainly interested in local seasons. In all performed simulations, a modern calendar is assumed. Although in reality the definition of seasons changes over time due to orbital precession, taking this calendar shift into account would only have a minor influence on our results since we calculate the summer and winter seasons by extracting the warmest and coldest month, respectively. Maximum and minimum LIG TS~~SATs~~ are calculated from the transient simulations considering the time interval between 130 and 120 kyr BP. In order to filter out internal variability, a 100-point running average representing the average over 1000 calendar years is applied. Maximum and minimum LIG warmth of the summer are defined as the warmest and coldest average of 100 warmest months, respectively, which reflects the warmest or coldest 1000 summer seasons with respect to the astronomical forcing. For the maximum and minimum LIG warmth of annual mean, we consider the warmest and coldest average of 100 model years, respectively. The seasonality range is defined by calculating the summer maximum LIG warmth (warmest average of 100 warmest months of the model years) and winter minimum LIG ~~SAT~~TS (coldest average of 100 coldest months of the model years).

2.3 Temperature reconstructions

In order to test the robustness of our simulations, we additionally perform a model-data comparison using proxy-based temperature anomalies that are available for the northern high latitudes (CAPE Last Interglacial Project Members, 2006), ~~and~~ across the ~~whole~~ globe (Turney and Jones, 2010), and in the northern and southern middle to high latitudes (Capron et al., 2014). The temperature reconstructions from CAPE Last Interglacial Project Members (2006) are based on terrestrial and marine proxy records and estimate summer temperatures for maximum LIG warmth relative to PI. The global dataset by Turney and Jones (2010) comprises terrestrial and marine proxy records and estimates annual mean temperatures for maximum LIG warmth (terrestrial) and for the period of plateaued $\delta^{18}O$ (marine), relative to present day (PD, 1961–1990; Smith and Reynolds, 1998; New et al., 1999). The dataset by Capron et al. (2014) used in our study comprises marine- and ice core-based temperature reconstructions at the 130 and 125 kyr BP, as well as covering the LIG (125–115 kyr BP). This temperature compilation is the first one to comprise temperature reconstructions associated with a coherent temporal framework built between the ice core and marine sediment records (Capron et al., 2014). Detailed information regarding the proxy data is given in CAPE Last Interglacial Project Members (2006), ~~and~~ Turney and Jones (2010), and Capron et al. (2014), respectively.

In order to quantify the agreement between model and data, we calculate the root-mean-square deviation (RMSD) which is a measure of the differences between an estimator (y_{model}) and estimated parameter (y_{data}) (Gauss and Stewart, 1995; Mudelsee, 2010). RMSD is defined in Eq. (2):

$$\mathrm{RMSD}=\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(y_{\mathrm{model}}-y_{\mathrm{data}}\right)^2} \tag{2}$$

where y_{model} is the ~~modelled~~simulated ~~SAT~~TS anomaly at the location of the proxy record, y_{data} indicates the reconstructed ~~SAT~~TS anomaly, and n is the number of data samples.

3. Results

In the first part of this section, we present results from our LIG GIS sensitivity simulations, focusing on TS anomalies. Afterwards, a short description of results from the transient simulations is presented, followed by the model-data comparison and consideration of potential uncertainties in the model and data.

3.1 ~~Insolation,~~ Greenland Ice Sheet elevation~~,~~ and albedo influence on global surface ~~air~~ temperature

3.1.1 Annual mean anomalies

W~~In the first part of this chapter, we~~e first focus on annual mean TS anomalies ~~of SAT~~. Figure 2~~a~~ presents the effect on the global TS of lowering the GIS by half its pre~~sent~~industrial elevation by various methods. ~~(LIG-×0.5), while maintaining the background albedo.~~ We observe ~~a~~the strongest warming over Greenland (of up to +~~11.1~~12.5°C) in the simulation with a reduction in GIS of 1300 m and albedo changes wherever the land surface is changed from ice-covered to tundra (LIG-1300m-alb, Figs. 1C and 2c). When reducing GIS by half its preindustrial elevation applying the first method described in Data and Methods section (LIG-×0.5 simulation, Figs. 1a and 2a), Greenland warms by up to +11.1°C. ~~and a warming of ~2°C over n~~Northern North America and the ~~western~~ Arctic Ocean warm by up to +2°C in all GIS sensitivity simulations. The most widespread warming is simulated in LIG-×0.5 (Fig. 2a), while the LIG-1300m-alb simulation presents a less widespread warming but a higher increase in TS over the Arctic Ocean, where anomalies of +2°C are simulated (Fig. 2c). ~~The Bering Sea warms by up to +3°C, while north-eastern Asia and the eastern part of the Arctic Ocean warm by up to +1°C.~~ A ~~There is also a~~ pronounced warming is found over the southernmost Southern Ocean of up to +4°C (Fig. 2a–c).

The highest global mean ~~global~~ ~~SAT~~TS anomaly is simulated in LIG-1300m-alb simulation with an average of Δ~~SAT~~TS = +0.37~~6~~°C, though is higher by only +0.01°C than the average derived from LIG-

×0.5 simulation, and by +0.07°C than LIG-1300m simulation. Changes in GIS configuration lead to strongest anomalies in ~~T~~the ~~NH~~Northern Hemisphere~~-~~, with average TS changes of ~~warms by~~ Δ~~SAT~~TS = +0.47°C in LIG-×0.5 simulation~~;~~, ΔTS = +0.38°C in LIG-1300m, and ΔTS = +0.43°C in LIG-1300m-alb simulation. T~~t~~he highest average TS changes in the Southern Hemisphere~~ (SH)~~ are simulated in LIG-1300m-alb with ΔTS = +0.31°C, while in LIG-1300m and LIG-×0.5 simulations the average TS anomalies are ΔTS = +0.20°C and ΔTS = +0.24°C, respectively~~by ΔSAT = +0.24°C~~. Consequently, the exact method of changing GIS configuration influences the hemispheric temperature anomalies.

The most affected areas by changes in GIS configuration are ~~T~~the northern high latitudes, which experience ~~the strongest~~a warming ~~with~~of Δ~~SAT~~TS = +1.45~~07~~°C in LIG-1300m-alb simulation~~.~~, and ΔTS = +1.07°C and ΔTS = +1.03°C in LIG-×0.5 and LIG-1300m simulations, respectively. This indicates that albedo plays a significant role in the northern high latitude temperature changes, causing an average temperature anomaly of ΔTS = +0.42°C. A local cooling of up to −1.60°C is limited to the Barents Sea in LIG-×0.5 and LIG-1300m simulations (Fig. 2a, b), south-west of Greenland in LIG-1300m simulation (Fig. 2b), and a cooling of up to −2.30°C over the Sea of Okhotsk (western Pacific Ocean) in LIG-1300m-alb simulation caused by a reduction in albedo in the prescribed ice-free areas (Fig. 2c, d). In the latter simulation, the Barents Sea cooling is counteracted by a warming caused by changes in albedo (Fig. 2d)~~with anomalies of ΔSAT = −1.60°C~~.

At 130 kyr BP, the AMOC was reduced by 3.5 Sv as compared to the PI (Table 2). However, a~~The~~ reduction in GIS partly counteracts the negative anomaly and leads to an~~ small~~ increase in the ~~Atlantic meridional overturning circulation (~~AMOC~~)~~ of ~~0.5~~up to 2.2 Sv relative to the control simulation LIG-ctl. The applied method of changing GIS configuration has an influence also on the simulated changes in AMOC. In the LIG-×0.5 simulation, there is rather a minor increase in AMOC of 0.5 Sv, while in LIG-1300m simulation AMOC is increased by 2 Sv. In the LIG-1300m-alb, AMOC is enhanced by 2.2 Sv, meaning that changes in albedo further contribute an increase of 0.2 Sv~~in the simulation LIG-×0.5; relative to PI, the AMOC decreases by 3.0 Sv~~ (Table 2).~~When the GIS is reduced by 1300 m of its present elevation while retaining the background albedo (LIG-1300 m), the effect is similar (Fig. 2b) but not as pronounced as for LIG-×0.5 (Fig. 2a). Average global and NH SAT anomalies are ΔSAT = +0.30°C and ΔSAT = +0.38°C, respectively. The SH experiences an average warming of ΔSAT = +0.20°C. Strongest warming occurs in the northern high latitudes, where we observe an average SAT anomaly of ΔSAT = +1.03°C. In the Barents Sea and south-west of Greenland, we observe a cooling of~~

~~up to ΔSAT = −1.60°C. In the simulation LIG-1300 m, the AMOC is 2.0 Sv stronger than in LIG-ctl, but 1.5 Sv weaker than in the PI (Table 2).~~

~~The effect of lowering the GIS by 1300 m, including albedo changes wherever the land surface is changed from ice-covered to tundra (LIG-1300 m-alb), indicates a slightly higher global warming of ΔSAT = +0.37°C (Fig. 2c) when compared to simulations LIG-×0.5 and LIG-1300 m (Fig. 2a, b). The NH warms by ΔSAT = +0.43°C, the SH by ΔSAT = +0.31°C. In northern high latitudes, the highest positive SAT anomalies are present with changes of ΔSAT = +1.45°C. The only region that cools due to the applied changes in boundary conditions is the Sea of Okhotsk. We observe an even higher increase in the AMOC, when both changes in GIS and albedo are applied, with a difference of 2.2 Sv in simulation LIG-1300 m-alb compared to LIG-ctl. The AMOC in LIG-1300 m-alb is weaker by 1.3 Sv than in the PI (Table 2).~~

~~In order to analyze the **effect of albedo changes in emerging ice-free areas, we compare simulation LIG-1300 m to LIG-1300 m-alb (Fig. 2d). It is evident that reduced albedo is causing a strong warming where the GIS retreats (up to + 5.3°C) and a cooling of −2.3°C over the Sea of Okhotsk. A mild warming of +0.5 to +2.0°C occurs over the Arctic Ocean, the Weddell Sea, and west of the Antarctic Peninsula. The impact of albedo changes (LIG-1300 m-alb minus LIG-1300 m) is ΔSAT = +0.07°C (globally), ΔSAT = +0.05°C (NH), and ΔSAT = +0.11°C (SH). The effect of albedo changes on the AMOC is minor (0.2 Sv, Table 2)**~~

3.1.2 Winter and summer mean anomalies

The seasonal effect of a reduced GIS elevation ~~and corresponding changes in albedo (LIG-1300 m-alb)~~ is strongest during local winter in ~~the high latitudes of~~ both hemispheres in all GIS sensitivity simulations(~~Fig. 3a~~Table 2). However, for simplicity we focus here only on the GIS sensitivity simulation that includes changes in GIS elevation and corresponding changes in albedo (LIG-1300m-alb, Fig. 3). The TS anomalies between the LIG control simulation LIG-ctl and the other two GIS sensitivity simulations (LIG-×0.5 and LIG-1300m) can be calculated from the TS averages given in Table 2. In the ~~NH~~Northern Hemisphere, winter ~~SAT~~TS changes by Δ~~SAT~~TS = +0.57°C. The corresponding change in the ~~SH~~Southern Hemisphere winter is Δ~~SAT~~TS = +0.39°C and the global average is Δ~~SAT~~TS = +0.48°C (Fig. 3a). The changes in GIS elevation and albedo lead to a winter warming of Δ~~SAT~~TS = +2.08°C in the northern high latitudes.

During summer, the ~~SAT~~TS anomaly is also positive but of lower magnitude, with an average of

Δ~~SAT~~TS = +0.24°C for ~~NH~~Northern Hemisphere, ~~SH~~Southern Hemisphere, and globally (Fig. 3b). The northern high latitudes warm during summer by Δ~~SAT~~TS = +0.46°C, which is a modest change compared to winter warming. Relatively strong ~~C~~cooling occurs over the Sea of Okhotsk and south-west of Greenland (Fig. 3~~a, b~~), again with the strongest effect being present during winter.~~solated cooling over northern Asia, the North Pacific Ocean, and the Arctic Ocean. There is i~~ The sea ice edge and 50 %-compactness isolines are subject to local poleward retreat in the case of changed GIS and albedo.

3.2 Combined effects of LIG forcings on global surface temperature

The combined effects on ~~SAT~~TS of reducing the GIS by 1300 m, adjusting albedo, and applying astronomical changes that represent an LIG climatic setting are presented in Fig. 4. Assuming linearity of the different climatic drivers, we can additionally split the anomaly of simulations PI and LIG-1300 m-alb-CH_4 (equivalent to simulation LIG-1300~~–~~m-alb, but with a CH_4 concentration adjusted to ~~simulation~~ PI simulation) into the isolated contributions of changes in elevation and~~,~~ albedo~~,~~ and in astronomical forcing. The anomaly caused by the astronomical forcing is calculated as the difference between the anomaly of LIG-1300m-alb-CH_4 and PI, and the anomaly of LIG-1300m-alb and LIG-ctl. Considering Table 2, we find that the magnitude of the astronomical forcing influence is stronger than the effects of lowering the GIS and respective adjustment of the albedo in the global average of annual mean TS, as well as the annual mean average over Northern Hemisphere (Fig. 4a). In the Southern Hemisphere, both forcings have equal contributions to changes in annual mean TS (Fig.4a).~~, with an annual mean global average SAT anomaly caused by astronomical forcing of ΔSAT = +0.44°C (Fig. 4a), calculated as the difference between the anomaly of LIG-1300 m-alb-CH_4 and PI, and the anomaly of LIG-1300 m-alb and LIG-ctl.~~ During winter, changes in GIS have the strongest influence globally and in the Northern Hemisphere, while in the Southern Hemisphere changes in astronomical forcing are dominant (Fig. 4b). During summer, there is an opposite pattern. Insolation changes are dominant globally and in the Northern Hemisphere, while the Southern Hemisphere is mostly influenced by changes in GIS and albedo (Fig. 4c). The strongest combined effect of insolation and changes in GIS and albedo occurs in the Northern Hemisphere during summer with an anomaly of ΔTS = +2.51°C. Globally, the combined effect leads to a warming of ΔTS = +1.34°C during summer. In the Southern Hemisphere, the strongest combined effect is simulated during winter with ΔTS = +1.08°C.

~~For the NH and SH, the annual averages induced by insolation changes are ΔSAT = +0.56°C and ΔSAT = +0.31°C, respectively.~~ The highest annual mean average ~~SAT~~TS anomaly due to the combined forcing is found over Greenland with up to Δ~~SAT~~TS = +13.9°C, while the strongest cooling caused by insolation is located over central Africa, the Arabian Peninsula, and India (locally Δ~~SAT~~TS = −5.3°C, Fig. 4a). ~~The combined effects of astronomical forcing, reduced GIS, and albedo contribute to a global SAT anomaly of ΔSAT = +0.81°C (calculated as the anomaly between simulations LIG-1300m-alb-CH_4 and PI), and hemispheric anomalies of ΔSAT = +0.99°C (NH) and ΔSAT = +0.62°C (SH). This leads to a retreat of sea ice with respect to PI as indicated by the isolines of the sea ice edge and 50 % sea ice compactness (Fig. 4a). The AMOC decreases by 1.9 Sv in the LIG-1300 -m-alb-CH_4 simulation with respect to PI.~~The winter (local minimum ~~SAT~~TS) of the LIG is in general cooler than the PI at northern low ~~and~~to middle latitudes, while at northern high latitudes and ~~southern low and middle latitudes~~Southern Hemisphere winter is warmer (Fig. 4b). ~~When the combined effects of the elevation, albedo change, and astronomical forcing are considered, the NH is modestly warmer (ΔSAT = +0.05°C), partly due to cancellation of the strong local warming (of up to ΔSAT = +14.1°C) over the northern high latitudes by the cooling (reaching ΔSAT = −5.5°C) over low and middle latitudes, especially over Asia and northern Africa. In the SH and globally, SAT anomalies are higher – ΔSAT = +1.08°C and ΔSAT = +0.56°C, respectively.~~ If we separate the astronomical effect from the GIS lowering and albedo changes, we can attribute to insolation a cooling of Δ~~SAT~~TS = −0.52°C in ~~NH~~Northern Hemisphere, and a warming of Δ~~SAT~~TS = +0.69°C in ~~SH~~Southern Hemisphere ~~and ΔSAT = +0.08°C globally~~. Due to warmer high latitudes, the sea ice edge and 50 % sea ice compactness isolines are located closer to the continents in LIG relative to PI (Fig. 4b).

Summer (local maximum ~~SAT~~TS) anomalies of the LIG with respect to PI are stronger than winter anomalies in the Northern Hemisphere (Fig. 4c). ~~The astronomical forcing contribution is ΔSAT = +1.10°C globally, ΔSAT = +2.27°C for NH, and ΔSAT = −0.07°C for SH. The three effects combined lead to a warming with respect to PI of ΔSAT = +1.34°C, ΔSAT = +2.51°C, and ΔSAT = +0.17°C for global average, NH, and SH, respectively.~~ Strongest continental summer ~~SAT~~TS anomalies are located in the ~~NH~~Northern Hemisphere (up to Δ~~SAT~~TS = +16.7°C). Locations where the LIG is cooler than PI are found at ∼10°N over Africa and at ∼25°N over India. Figure 4c also depicts the locations of the sea ice edge and the 50 % sea ice compactness isolines, which indicate that, in the Arctic Ocean, LIG summer sea ice is more strongly reduced compared to PI than winter sea ice. The summer LIG Arctic Ocean sea ice cover does not exceed 50 %-compactness anywhere. In the Southern Ocean there is no such clear seasonal bias.

3.3~~2~~ ~~Northern Hemisphere s~~Surface ~~air~~ temperature evolution during the present and Last Interglacial ~~and the Holocene~~

In Figs. 5~~–7~~, S2, and S3, a comparison of transient ~~SAT~~TS derived from the five transient simulations (Table 1) is shown. The LIG transient simulations are important for determining when the maximum LIG warmth occurred in dependence of the location as well as seasons. For simplicity, we display here only ~~T~~the ~~SAT~~TS evolution in the northern high latitudes (60–90°N~~) is plotted in~~, Fig. 5). All LIG (130–115 kyr BP) simulations (LIG-ctl-tr, LIG-×0.5-tr, LIG-1300m-alb-tr, and LIG-GHG-tr) indicate a similar annual mean trend, starting with a plateau until mid-LIG (around 123 kyr BP) ~~during which there is only a small increase in the SAT trend of +0.1 to +0.5°C, the exact amplitude depending on the simulation~~. After mid-LIG, there is a pronounced cooling trend ~~of −3.4 to −4.4°C~~in all LIG transient simulations (Fig. 5a). The control simulation LIG-ctl-tr starts at a slightly higher ~~SAT~~TS than the LIG-GHG-tr, but although the trace gas concentrations are mostly lower throughout the latter, the LIG-GHG-tr simulates higher ~~SAT~~TS~~s~~ throughout the LIG. This indicates that changes in the vegetation which are simulated in the LIG-ctl simulation lead to a cooling in the Northern Hemisphere, partly counteracting the warming induced by higher GHG concentrations. Even warmer ~~SAT~~TS~~s~~ are observed in the LIG-×0.5-tr, due to the changes in GIS elevation. The most extreme case is represented by the simulation LIG-1300~~-~~m-alb-tr, which shows predominantly the highest ~~SAT~~TS~~s~~ relative to ~~SAT~~TS~~s~~ of other LIG transient simulations. When calculating the linear ~~SAT~~TS trends over 15 kyr covering the LIG (130–115 kyr BP), simulation LIG-×0.5-tr presents the steepest trend with a value of −3.97°C~~, followed by LIG-1300 m-alb-tr with a cooling trend of −3.73°C, and LIG-ctl-tr with −3.47°C~~. LIG-GHG-tr represents the weakest trend, namely −2.95°C. The Holocene (8–0 kyr BP) transient simulation (HOL-tr) starts also with a warming (+1.45°C) until around mid-Holocene (6 kyr BP), followed by a cooling trend. The trend over the last 8 kyr is negative, with a value of −1.76°C.

During winter, all LIG simulations indicate a positive trend ~~of +1.7 to +2.7°C~~ in the early LIG, with maximum ~~SAT~~TS~~s~~ at around mid-LIG (Fig. 5b)~~. The warming is~~, followed by a strong cooling ~~of −3.4 to −5.6°C~~. The relative order of magnitudes of ~~SAT~~TS trends during different simulations is the same as for annual mean ~~SAT~~TS~~s~~, but with a relatively larger offset in between simulations. The strongest winter ~~SAT~~TS trend during the LIG is present in simulation LIG-×0.5-tr, with a cooling of −2.47°C. ~~In simulation LIG-1300 m-alb-tr, a trend of −1.94°C is present, while LIG-ctl-tr and~~The smallest trend is simulated in LIG-GHG-tr simulation ~~are characterized by trends of −1.55 and~~, namely −1.08°C~~, respectively~~. Simulation HOL-tr shows a warming of +0.8°C, followed by a cooling trend that starts at mid-Holocene (Fig. 5b). Overall, the Holocene ~~SAT~~TS trend is −1.73°C. Winter ~~SAT~~TS~~s~~ are characterized by stronger temporal variability than summer ~~SAT~~TS~~s~~ (Fig. 5b, c).

~~Warmest month~~Summer ~~SAT~~TS~~s~~ in all LIG simulations indicate a slight warming trend ~~of +0.2 to +0.6°C~~ until around 128 to 126 kyr BP, followed by a pronounced cooling~~ of −5.8 to −6.1°C~~. The strongest trend during summer is present in simulation LIG-ctl-tr (−6.26°C)~~. The other transient simulations produce similar trends of −6.06°C (LIG-1300 m-alb-tr), −6.02°C (LIG-×0.5-tr), and~~, while the smallest is derived from LIG-GHG-tr simulation (−5.94°C)~~ (LIG-GHG-tr)~~. The offset between transient ~~SAT~~TS~~s~~ is smaller than for annual mean and winter, but with the same order on the temperature scale. A dramatic cooling is also present in the Holocene simulation, which shows a trend of −2.28°C starting at mid-Holocene (Fig. 5c). Furthermore, the timing of the maximum LIG warmth does not occur simultaneously between the winter and summer seasons, the winter season indicating a later peak than summer (Figs. 5, S2, andS3).

~~In northern middle latitudes (Fig. 6), both trends and offsets are of a smaller magnitude than in high latitudes, but in the same order with respect to magnitude. In annual mean, winter, and summer, there is a small offset between LIG simulations, the warmest realization being LIG-1300 m-alb-tr and the coolest realization being LIG-ctl-tr (Fig. 6). Annual mean SATs are characterized by a small cooling trend for all five transient simulations (Fig. 6a). The strongest cooling trend is present in simulation LIG-×0.5-tr (−0.88°C), followed by simulations LIG-1300 m-alb-tr (−0.73°C) and LIG-ctl-tr (−0.53°C). Simulation LIG-GHG-tr exhibits the smallest trend of −0.41°C. The Holocene is also characterized by a cooling trend of −0.53°C. Winter SATs are subject to a warming trend of +2.8 to +3.3°C until 118 kyr BP, followed by a modest cooling of −0.3 to −0.6°C. The strongest warming trend in the winter season is present in simulation LIG-GHG-tr (+2.99°C). The other LIG transient simulations are characterized by slightly smaller trends: +2.93°C (LIG-ctl-tr), +2.62°C (LIG-1300 m-alb-tr), and +2.35°C (LIG-×0.5-tr). The Holocene simulation warms by +0.15°C (Fig. 6b). Summer SATs indicate the most dramatic trends (Fig. 6c). After a small warming of +0.4 to +0.9°C that occurs until around 128 kyr BP, the SAT drops by −6.7 to −7.1°C. The LIG SAT trends simulated by our model setup are: −7.18°C (LIG-×0.5-tr), −7.08°C (LIG-1300 m-alb-tr), −6.92°C (LIG-ctl-tr), and −6.72°C (LIG-GHG-tr). During the Holocene, we notice a clear cooling trend that is of a lower magnitude than trends during the LIG (−2.49°C).~~

~~In the northern low latitudes, annual mean SAT trends indicate a modest warming of + 0.7 to +0.8°C (Fig. 7a). During the LIG, the winter SAT increases by +2.3 to +2.5°C until around 117 kyr BP, after~~

which the trend reverses to a modest cooling of −0.1°C. Simulation LIG-GHG-tr indicates the strongest trend of +2.51°C over the LIG, followed by LIG-ctl-tr (+2.43°C), LIG-1300 m-alb-tr (+2.36°C), and LIG-×0.5-tr (+2.32°C). During the Holocene, winter SATs modestly warm by +0.53°C (Fig. 7b). In the early LIG, a small summer warming of +0.1 to + 0.4°C is simulated with the SAT maximum located at around 128 kyr BP. After the peak, the trends indicate a cooling of −1.3 to −1.4°C (Fig. 7c). The strongest trend of −1.39°C is present in simulation LIG-×0.5-tr. The other simulations indicate similar slightly smaller trends: −1.34°C (LIG-1300 m-alb-tr), −1.30°C (LIG-ctl-tr), and −1.19°C (LIG-GHG-tr). Again, for annual mean, winter, and summer simulation LIG-1300 m-alb-tr is warmest, although the SAT offset between simulations is even smaller at low latitudes (Fig. 7)

3.34 Comparison of model results to proxytemperature reconstructions

Due to the large amount of simulated data, we display in the model-data comparison simulated LIG TS derived from only one equilibrium simulation with changes in GIS, namely LIG-1300m-alb. For the calculation of the maximum LIG warmth, we consider the corresponding LIG-1300m-alb-tr transient simulation. However, the comparison of the proxy-based temperatures with the other GIS sensitivity simulations is considered in Table S1 in the Supplementary material, which gives the RMSD values between temperature reconstructions and simulated TS extracted at the location of each given proxy record and derived from simulations with different GIS boundary conditions. Furthermore, we display also results from LIG-ctl equilibrium simulation for 130 kyr BP and LIG-ctl-tr transient simulation for maximum LIG warmth, in order to determine if and where GIS changes lead to an increase in model-data agreement.

3.4.1 Proxy-based summer temperature reconstructions

Figures 68–10, 8a, and S4a present a model-data comparison ofthat consider LIG terrestrial and marine proxy-based summer temperature anomalies relative to PI derived by CAPE Last Interglacial Project Members (2006). The terrestrial and marine proxy records are derived by CAPE Last Interglacial Project Members (2006) (Figs. 8 and 10a) and Turney and Jones (2010) (Figs. 9 and 10b, c). Figure 8a depicts summer temperature anomalies in the northern high latitudes at the beginning of the LIG (130 kyr BP). The results therefore reflect the influence of a reduced GIS, adjusted albedo, insolation, and a lower methane concentration.).10) and the minimum LIG warmth (also indicated in Fig. 109b, and b, 8m-alb-tr for the maximum (Figs.), and from simulation LIG-130010 and , 9a,a8m-alb for 130 kyr BP (Figs. is calculated from the simulation LIG-1300SAThe simulated LIG T ModelledSimulated and reconstructed temperature anomalies agree reasonably well with respect to the sign of the change, in the simulation with a reduction in GIS (Fig. 6a) and with preindustrial GIS configuration (Fig. 6c). Over northern AsiaThe best, agreement between model and proxy reconstructions occurs over northern Asia and Europe and Great Britain is best, good agreement is also present across Europe. In the North Atlantic Ocean and the Arctic Ocean, the modelsimulation underestimates marine-based temperature reconstructions (Fig. 6a, c). There is nearly no SATTS change present in the model, while the marine records indicate anomalies of +1 to +4°C. However, a reduction in GIS and albedo leads to slightly higher summer temperature anomalies at the location of some marine proxies in the North Atlantic Ocean, partly reducing the model-data mismatch (Fig. 6a).

Over Greenland, the elevation changes lead to an overestimation of anomalies are higher than SAT modelledthe the reconstructed temperature anomalies – proxy records show anomalies of +4 to +5°C, while the modelledsimulated SATTS anomalies are higher (above +7°C (Fig. 6a)). In the control simulation, LIG-ctl, there is an underestimation of the reconstructed temperatures (Fig. 6c). In the west of Greenland, the model underestimates the terrestrial proxy records by about 5°C, with the exception of one terrestrial record located on Baffin Island. An overestimation of the proxy reconstruction by the model is present over Alaska, where the modelledsimulated SATTS changes in the LIG-1300m-alb simulation are within +3 to +4°C, while the terrestrial proxy-based temperature anomalies are between +0 and +2°C. However, in the LIG-ctl simulation, the differences between model and data are smaller. Although not all the records agree with model data regarding the magnitude of the temperature anomaly, the sign of the anomaly is generally comparable (Figs. 8 and 10a).

In addition to the 130 kyr BP LIG simulation (LIG-1300m-alb), for each given core location we also consider TS anomalies relative to PI calculated at the minimum and maximum LIG summer warmth as derived from the transient simulation LIG-1300m-alb-tr (Fig. 8a). In the case of the terrestrial proxies, the temperature span covers +2 to +6°C, but 0 to +10°C (Fig. 8a) if we consider the uncertainty temperature intervals from which we chose the values closest to corresponding model results. The respective simulated anomalies cover +1 to +11°C, the largest anomalies being located over Greenland (Fig. 6a). When we consider also the simulated TS anomalies at the summer minimum and summer maximum LIG warmth for each record, in about half the cases (14 records out of 27) the error bars touch the 1 : 1 line, possibly indicating better agreement than when compared to LIG TS anomalies at 130 kyr BP (Fig. 8a). The number of 13 unresolved records can be reduced to 11, when the terrestrial proxy-based temperature anomalies are compared to the simulated TS anomalies that are derived from the simulation with PI GIS elevation (LIG-ctl-tr, Fig. S4a). Marine-based temperature anomalies and the corresponding simulated anomalies (from LIG-1300m-alb) are of lower magnitude than their terrestrial counterparts, with a marine-based temperature anomaly span of 0 to +3°C (and 0 to +4°C temperature uncertainty) and simulated TS anomaly span of ~0 to +4°C (Fig. 8a). Only one marine record, located on the eastern coast of Greenland, shows an underestimation of at least 6°C (Fig. 6). Seven out of thirteen marine records cannot be reconciled with the simulations when considering maximum and minimum summer TS anomalies during the LIG (Fig. 8a). The LIG-ctl-tr simulation as well can resolve only 6 records (Fig. 6d and S4a). When the reconstructed data is compared to simulated annual mean TS anomalies at 130 kyr BP (Figs. S5a, c and S6), we find an even higher discrepancy than when compared to the summer average, implying that the reconstructed records are indeed biased towards summer. Furthermore, there are 20 terrestrial and 8 marine records that cannot be resolved by using annual mean minimum or maximum LIG warmth in the LIG-1300m-alb-tr (Figs. S5b and S6a), and 21 terrestrial and 8 marine records in the LIG-ctl-tr (Figs. S5d and S6b).

~~= +3.11°C. SATThe LIG summer in the northern middle to high latitudes (between 50 and 90°N) is much warmer than the PI, with an average anomaly of Δ~~The proxy dataset by CAPE Last Interglacial Project Members (2006) is considered to represent summer temperatures at the maximum LIG warmth. Thus, we additionally include in the model-data comparison the simulated maximum LIG warmth calculated from our transient LIG simulations (Fig. 6b, d). ~~anomalies at maximum LIG warmth are considered (Fig. 8b),SATWhen instead summer~~ We find that the agreement between model and data increases in some cases. Over northern Asia, for example, highest simulated summer ~~SAT~~TS anomalies occur between 126.5 and 129.5 kyr BP (Fig. 9~~11~~a), and~~that~~ are in better agreement with the proxy records than when ~~compared to the~~ simulated anomalies ~~from the beginning of the LIG~~ at ~~(~~130 kyr BP are considered~~)~~. ~~The terrestrial records located west of Greenland are also in better agreement with the simulation when maximum LIG warmth is considered.~~ For the northern North Atlantic Ocean, marine records agree best with ~~modelled~~simulated ~~SAT~~TS anomalies at the maximum LIG warmth (between 121.5 and 124.5 kyr BP, Fig. 9~~11~~a) in the LIG-1300m-alb simulation (Fig. 6b). However, the RMSD between the simulated TS and reconstructed temperature anomalies reveals that the best agreement occurs with TS anomalies at maximum LIG warmth in the LIG-ctl-tr simulation (Table S1 in Supplementary material). A reduction in GIS, thus, does not improve in general the model-data agreement when the dataset by CAPE Last Interglacial Project Members (2006) is considered. However, changes in GIS lead to high temperature anomalies during local winter (Fig. 3a), while summer season is not strongly influenced (Fig. 3b). Therefore, in a comparison with proxy reconstructions that represent summer temperature anomalies, changes in GIS do not have a significant impact on model-data agreement. anomalies is relatively large, the model presenting anomalies of up to +4°C (Fig. 8b).SAT modelledOver Alaska, the difference between terrestrial proxy-based temperature anomalies and

3.4.2 Proxy-based annual mean temperature reconstructions

Both reconstructed and simulated global annual mean temperature anomalies (Fig. 79) indicate that the high latitudes experienced warmer temperatures during the LIG than in the PI, with strongest anomalies being present in the northern high latitudes especially over Greenland and the Arctic Ocean. However, the model underestimates the strong positive anomalies derived from proxy records, and iIn low and middle latitudes the model cannot capture the magnitude of the cooling that the proxy records show (Figs. 79a, c, and 810b, and S4b). Cooling in the model is restricted to central Africa, the Arabian Peninsula, South-East Asia, and India, while warming in low and middle latitudes occurs mainly over land and at large parts of the Pacific Ocean (Fig. 9a). b).10 and proxy-based anomalies are of the same sign. Both suggest a strong warming, but the model underestimates the anomalies derived from proxy records (Figs. 9 and modelledIn northern high latitudes, the

Changes in GIS have no significant influence in low to middle latitudes but cause strong positive anomalies in the northern high latitudes thus improving the model-data comparison (Fig. 7a, Table S2), although the model still underestimates the proxy reconstructions. = +0.61°C, respectively.SAT = +0.65°C and ΔSAT experience similar magnitudes of ΔSH and NH = +0.63°C. The SATGlobally, the model shows an annual mean average warming of Δ Terrestrial proxy records indicate a warming, but of higher magnitude,stronger anomalies with ΔSATTS = +2.21°C (globally), ΔSATTS = +2.21°C (NHNorthern Hemisphere), and ΔSATTS = +2.11°C (SHSouthern Hemisphere). Consideration of the simulated anomalies at locations of terrestrial records indicates a global average of ΔSATTS = +1.44°C, underestimating the records by ∼1°C. The NHNorthern Hemisphere and SHSouthern Hemisphere average SATTS anomalies are ΔSATTS = +1.48°C and ΔSATTS = +0.92°C, respectively. Marine records capture lower anomalies than their terrestrial counterparts but still larger anomalies than the corresponding simulated anomalies. .S = +0.27°C in SAT, and ΔNH = +0.44°C in SAT = +0.37°C (globally), ΔSAT). The corresponding average model anomalies are ΔSH = +0.72°C (SAT), and ΔNH = +0.86°C (SAT = +0.80°C (globally), ΔSAT, with Δ

The majority of the terrestrial records shows a stronger signal than the simulated anomalies (Fig. 8b). The temperature anomaly range in the terrestrial reconstructed data covers −5 to +15°C, while the model covers 0 to +12°C. The proxy records that indicate the most extreme negative temperature anomalies (31 records out of 100) are not fully reconciled with simulations by considering the minimum LIG values derived from the model. For positive temperature anomalies, there are 36 records that agree better with the model simulation when the maximum LIG warmth is considered, but the error bars do no touch the 1 : 1 line indicating as well a persistent deviation (Fig. 4b). The remaining 33 terrestrial records agree with the model data somewhere between the annual mean minimum and maximum LIG warmth. This is a slightly better result than for simulation LIG-ctl-tr, in which case only 19 terrestrial records can be resolved by considering minimum and maximum TS intervals (derived from LIG-ctl-tr, Figs. S3d and S4b). When we consider marine proxy-based temperature anomalies, the model-data agreement is lower than in the case of their terrestrial counterparts. The reconstructed marine temperature anomalies cover a range of −6 to +11°C compared to 0 to +3°C in the model, indicating pronounced underestimation of the marine proxy-based anomalies by the model. Low temperature anomalies are mostly located at low latitudes, where the magnitude of temperature change is higher in the reconstruction than in the model (Figs. 7a and 8b). When we consider both annual mean minimum and maximum LIG warmth, the simulated TS span increases by ∼1°C (−0.5 to +3.5°C). Considering the annual mean maximum LIG warmth, 71 (out of 162) marine records that show positive anomalies cannot be reconciled with the simulation. From the records that show negative anomalies, 71 cannot be resolved by TS anomalies at minimum LIG. The remaining 20 records agree with the model data between the minimum and maximum LIG warmth with respect to annual mean. The marine records are slightly better reconciled when LIG-ctl-tr is considered, with 25 records being reconciled with the simulation by the minimum and maximum LIG warmth (LIG-ctl-tr, Fig. S4b).

The proxy records derived by Turney and Jones (2010) are considered to record an annual mean temperature signal. Nevertheless, some records may be biased towards a specific season. Therefore, we also consider the minimum winter and maximum summer TS during the LIG (Fig. 4c). Seasonality increases the span of the vertical bars, providing the possibility of a better agreement with the reconstructed temperature anomalies. The agreement between proxy records and model simulations increases, with 51 terrestrial and 53 marine records being reconciled by considering seasonality (Fig. 4c). An even better agreement is found when the terrestrial proxy-based temperature anomalies are compared to the simulated seasonality range derived from simulation LIG-ctl-tr. In this case, for 69 terrestrial records the vertical bars touch the 1 : 1 line (Fig. 4c). For the marine proxies a number of 51 records can be reconciled with the simulation by considering seasonality as derived from simulation

LIG-ctl-tr.

As already mentioned, ~~T~~the terrestrial proxy records by Turney and Jones (2010) are considered to record annual mean temperature anomalies at the maximum LIG warmth. Therefore, we additionally compare the terrestrial records with the simulated annual mean at the LIG thermal maximum (Fig. 7~~9~~b, d). Over Europe, the agreement between model and data is increased for those records that indicate a warming, as the modelled~~simulated~~ anomalies derived from LIG-1300m-alb-tr simulation indicate a warming at the maximum LIG warmth, while presenting nearly no change at ~~the beginning of the LIG (~~130 kyr BP~~,~~ (Fig. 7~~9~~a). Over northern Europe, maximum LIG warmth occurs at mid-LIG between 122.5 and 123.5 kyr BP (Fig. 9~~11~~b). There is a slightly better agreement for the records located in northern Asia. At these locations, the highest ~~SAT~~TS anomalies are found towards the first part of the LIG (between 126.5 and 129.5 kyr BP). According to Table S2 in the Supplementary material, the terrestrial proxy-based temperature anomalies indicate the best agreement with the simulated annual mean TS at the maximum LIG warmth derived from the LIG-1300m-alb simulation. The annual mean anomalies are influenced by winter temperatures, the season during which GIS leads to strong positive anomalies. Therefore, a model-data comparison with proxy reconstructions that represent an annual mean signal shows a better agreement than when summer proxies are considered. ~~seasonality range derived from simulation LIG-ctl-tr. In this case, for 69 terrestrial records the vertical bars touch the 1 : 1 line (Fig. S8c). For the marine proxies a number of 51 records can be reconciled with the simulation by considering seasonality as derived from simulation LIG-ctl-tr.modelled during the LIG (Fig. 10c). Seasonality increases the span of the vertical bars, providing the possibility of a better agreement with the reconstructed temperature anomalies. The agreement between proxy records and model simulations increases, with 51 terrestrial and 53 marine records being reconciled by considering seasonality (Fig. 10c). An even better agreement is found when the terrestrial proxy-based temperature anomalies are compared to the SAT~~

~~The proxy records derived by Turney and Jones (2010) are considered to record an annual mean temperature signal. Nevertheless, some records may be biased towards a specific season. Therefore, we also consider the minimum winter and maximum summer anomalies at minimum LIG. The remaining 20 records agree with the model data between the minimum and maximum LIG warmth with respect to annual mean. The marine records are slightly better reconciled when LIG-ctl-tr is considered, with 25 records being reconciled with the simulation by the minimum and maximum LIG warmth (LIG-ctl-tr, Fig. S8b).SAT span increases by ~1°C (−0.5 to +3.5°C). Considering the annual mean maximum LIG~~

warmth, 71 (out of 162) marine records that show positive anomalies cannot be reconciled with the simulation. From the records that show negative anomalies, 71 cannot be resolved by SAT modelled in the case of their terrestrial counterparts. The reconstructed marine temperature anomalies cover a range of −6 to +11°C compared to 0 to +3°C in the model, indicating pronounced underestimation of the marine proxy-based anomalies by the model. Low temperature anomalies are mostly located at low latitudes, where the magnitude of temperature change is higher in the reconstruction than in the model (Figs. 9a and 10b). When we consider both annual mean minimum and maximum LIG warmth, the not as good as intervals (derived from LIG-ctl-tr, Figs. S7b and S8b). When we consider marine proxy-based temperature anomalies, the model-data agreement is SAT anomalies. The temperature anomaly range in the terrestrial reconstructed data covers −5 to +15°C, while the model covers 0 to +12°C. The proxy records that indicate the most extreme negative temperature anomalies (31 records out of 100) are not fully reconciled with simulations by considering the minimum LIG values derived from the model. For positive temperature anomalies, there are 36 records that agree better with the model simulation when the maximum LIG warmth is considered, but the error bars do no touch the 1 : 1 line indicating as well a persistent deviation (Fig. 10b). The remaining 33 terrestrial records agree with the model data somewhere between the annual mean minimum and maximum LIG warmth. This is a slightly better result than for simulation LIG-ctl-tr, in which case only 19 terrestrial records can be resolved by considering minimum and maximum modelledm-alb-tr), the latter being plotted as vertical bars (Fig. 10b). The majority of the terrestrial records shows a stronger signal than the m-alb) as well as to the annual mean minimum and maximum LIG warmth (LIG-1300 anomalies at 130 kyr BP (LIG-1300SAT

Terrestrial and marine proxy records derived by Turney and Jones (2010), representing annual mean anomalies with respect to PI, are compared to simulated corresponding annual mean m-alb-tr (Figs. S9c and S10a), and 21 terrestrial and 8 marine 10 records in the LIG-ctl-tr (Figs. S9d and S10b). anomalies at 130 kyr BP (Figs. S9a, b and S10), we find an even higher discrepancy than when compared to the summer average, implying that the reconstructed records are indeed biased towards summer. Furthermore, there are 20 terrestrial and 8 marine records that cannot be resolved by using annual mean minimum or maximum LIG warmth in the LIG-1300SAT anomalies during the LIG (Fig. 10a). The LIG-ctl-tr simulation as well can resolve only 6 records (Figs. S6b and S8a). The summer maximum and minimum LIG anomalies alone represent an overestimation and underestimation, respectively, of the reconstructed data by the model. When the reconstructed data is compared to simulated annual mean SAT anomalies by the terrestrial records located over Greenland (Fig. 8). Seven out of thirteen marine records cannot be reconciled with the simulations when considering maximum and minimum summer SAT anomaly span of ~0 to +4°C (Fig. 10a). Only one marine record, located on the eastern coast of Greenland, shows an underestimation of at least 6°C similar to the underestimation of the model SAT modelledm-alb) are of lower magnitude than their terrestrial counterparts, with a marine-based temperature anomaly span of 0 to +3°C (and 0 to +4°C temperature uncertainty) and anomalies (from LIG-1300modelled anomalies that are derived from the simulation with PI GIS elevation (LIG-ctl-tr, Figs. S6b and S8a). Marine-based temperature anomalies and the corresponding SAT modelled anomalies at 130 kyr BP (Fig. 10a). The number of 13 unresolved records can be reduced to 11, when the terrestrial proxy-based temperature anomalies are compared to the SAT anomalies at the summer minimum and summer maximum LIG warmth for each record, in about half the cases (14 records out of 27) the error bars touch the 1 : 1 line, possibly indicating better agreement than when compared to LIG SAT anomalies cover +1 to +11°C, the largest anomalies being located over Greenland where the model overestimates the proxy by ~6°C. With the exception of Greenland and Alaska, there is mostly an underestimation of the proxy-based anomalies by the model (Figs. 8a and 10a). When we consider also the simulated modelled anomalies shown in Fig. 8. In the case of the terrestrial proxies, the temperature span covers +2 to +6°C, but 0 to +10°C (Fig. 10a) if we consider the temperature uncertainty intervals from which we chose the values closest to corresponding model results. The respective SAT northern high latitudes summer modelledm-alb-tr (Fig. 10). In Fig. 10a, proxy-based maximum summer LIG temperature anomalies by CAPE Last Interglacial Project Members (2006) are plotted against as derived from the transient simulation LIG-1300SATs anomalies relative to PI calculated at the minimum and maximum of LIG SATm-alb), for each given core location we also consider). In addition to the 130 kyr BP LIG simulation (LIG-130010 is also displayed via scatter plots (Fig. 9 and 8

The model-data comparison of Figs. m-alb-tr as compared to $RMSD_{marine}$ = 1.40°C for LIG-ctl-tr). m-alb-tr as compared to $RMSD_{terrestrial}$ =1.16°C for LIG-ctl-tr; $RMSD_{marine}$ = 2.26°C for LIG-1300 derived from LIG-ctl and LIG-ctl-tr, especially when warmest month at the maximum LIG warmth is considered ($RMSD_{terrestrial}$ = 2.54°C for LIG-1300SATsThe data derived by CAPE Last Interglacial Project Members (2006) shows a better agreement with m-alb-tr as compared to $RMSD_{marine}$ = 3.47°C for LIG-ctl-tr). m-alb-tr as compared to $RMSD_{terrestrial}$ = 3.21°C for LIG-ctl-tr; $RMSD_{marine}$ = 3.43°C for LIG-1300 m-alb-tr), especially when annual mean at the maximum LIG warmth is considered

(RMSD$_{terrestrial}$=3.12°C for LIG-1300 m-alb, LIG-1300 anomalies derived from the simulation with PI GIS boundary conditions (LIG-ctl, Figs. S6–S8). We find that both the terrestrial and marine temperature anomalies by Turney and Jones (2010) agree slightly better with the anomalies derived from the simulations with reduced GIS elevation (LIG-1300SAT

In order to check whether indeed a reduced GIS elevation improves the agreement with the reconstructed data, we also plot the

3.4.2 Time resolved proxy-based summer temperature reconstructions

For a more robust model-data comparison, we additionally compare our simulated TS to a compilation of high-latitude LIG temperature anomalies derived from synchronized records representing 130 kyr BP (Figs. 10 and S12, Capron et al., 2014). The synchronization is performed by aligning marine sediment records onto the recent AICC2012 ice chronology (Capron et al., 2014 and references therein). This method reduces the uncertainty in relative dating of the proxy reconstructions. The temperature reconstructions are mostly located in the North Atlantic Ocean and Southern Ocean. The marine records from the North Atlantic Ocean indicate mostly negative anomalies, while the model simulates nearly no changes. As shown above, GIS reduction leads to a small increase in summer TS anomalies, thus increasing the model-data disagreement (Figs. 10a and S12a). A warming in the Southern Ocean is captured by both the model and proxies, though the model underestimates the reconstructions. Reducing the GIS and albedo leads to an increase in local summer TS anomalies in the Southern Ocean bringing the model and data in slightly closer agreement (Figs. 10b and S12b).

Considering Table S3 in Supplementary material, the reconstructed temperatures agree best with the simulated summer TS at 125 kyr BP in simulation LIG-125k (Fig. S15) which considers a reduced GIS configuration (as in the LIG-1300m-alb simulation), both indicating a warming. However, this result is not conclusive with respect to the GIS elevation, as a simulation with preindustrial GIS elevation has not been yet performed for this particular time slice. For 130 kyr BP, the best agreement occurs for the LIG-ctl simulation but for annual mean rather than summer; since the model simulates an annual mean cooling in the North Atlantic Ocean (Fig. S5c).

The proxy record compilation is used in the model-data comparison by Capron et al. (2014), using two different climate models, namely CCSM3 and HadCM3. For 130 kyr BP, a model-data mismatch is found in both cases, as most of the records indicate strong negative anomalies at 130 kyr BP, while the models simulate strong positive anomalies, especially CCSM3 which simulates higher GHG concentrations than HadCM3 and COSMOS. With respect to difference between model and data, COSMOS simulates TS closer to the temperatures derived from marine-based records, since it simulates nearly no change rather than a strong opposite signal. One cause for this modest change in the North Atlantic Ocean may be related to vegetation changes, which may lead to a cooling as suggested above. For 125 kyr BP, COSMOS simulates higher anomalies in the North Atlantic Ocean than at 130 kyr BP, but lower than CCSM3 and HadCM3 which simulate SSTs closer to the reconstructed temperatures. Note that the definition of summer is different in our study than in the study by Capron et al. (2014), as they calculate it as the average of July-August-September, while we consider the warmest month.

A model-data comparison of LIG temperature trends is also considered in our study (Figs. S13 and S14). The proxy-based temperature trends by Capron et al. (2014) is compared to the temperature evolution derived from our transient simulations (LIG-ctl-tr and LIG-1300m-alb-tr), between 125 and 115 kyr BP. An underestimation of the proxies by the model is again found, as well as an overestimation depending on the locations (Figs. S13 and S14). Changes in GIS do not strongly influence the results, with the exception of a few locations where such changes lead to a less pronounced warming simulated in LIG-ctl-tr, thus reducing the mismatch.

4. Discussion

4.1 Effects of iInsolation ~~effects~~and Greenland Ice Sheet elevation on surface temperature

The main focus of our study is to quantify the possible contribution of reduced GIS elevation in comparison~~bination~~ with the contribution of insolation forcing to the climate of the LIG. ~~In all performed simulations, a modern calendar is assumed. Although in reality the definition of seasons changes over time due to orbital precession, taking this calendar shift into account would only have a minor influence on our results. It is known that one main driver for LIG climate is the Earth's astronomical parameters (Kutzbach et al., 1991; Crowley and Kim, 1994; Montoya et al., 2000; Felis et al., 2004; Kaspar and Cubasch, 2007). During the early part of the LIG, the axial tilt (obliquity) was higher which caused stronger summer insolation at high latitudes, while the low latitudes received less insolation; this effect manifests in enhanced seasonality (i.e. warmer summers and cooler winters) in the LIG climate.~~

We can confirm the importance of insolation for the ~~NH~~Northern Hemisphere, especially for the northern middle to high latitudes (Figs. 4, ~~8~~6, ~~7~~9, 10 ~~S1, S3, S4, S6, S7, S9, S11, S12, S15, and S16~~).

The belt of decreased ~~SAT~~TS~~s~~, observed around 10°N over Africa and 25°N over Arabian Peninsula and India (Figs. 4a, b and 7~~9~~a), is related to increased cloud cover (Fig. S9~~14~~) and increased summer precipitation of up to +6 mm d^{-1} (not shown). This effect has been described by Herold and Lohmann (2009), who propose a mechanism for the temperature anomalies that relies on changes in insolation in conjunction with increased cloud cover and increased evaporative cooling.

In general, and independent of GIS elevation we observe an annual mean global warming of ΔTS= +0.44°C in our LIG simulations relative to PI, hinting to positive feedbacks (such as sea ice-albedo) that amplify the high latitude insolation signal (Fig. 4).~~ **temperature airInfluence of Greenland Ice Sheet elevation on surface**~~

~~**4.2**~~

~~In all LIG GIS sensitivity simulations, we observe widespread warming in the northern middle to high latitudes (Fig. 2a–e).~~

In Section 3.1.2 we have shown that ~~T~~the most pronounced impact of reduced GIS elevation (in LIG-1300m-alb simulation) occurs during local winter in both hemispheres~~m-alb in simulation LIG-1300~~ (Fig. 3a). The winter warming of up to +3°C over the Arctic Ocean may be linked to a decrease in sea ice~~. in combination with atmospheric changes~~ and a delayed response to a warming occurring in October (not shown) which is caused by positive sea-ice-albedo feedbacks. A decrease in albedo over Greenland has the strongest influence during summer especially over the southernmost region (Figs. 2d and 3b), caused by insolation absorption by the ice-free land surface. Furthermore, we note cold annual mean anomalies in the Barents Sea (Fig. 2a, b) and Sea of Okhotsk (Fig. 2c) caused by an increase~~d~~ in sea ice cover.~~m in simulations LIG-×0.5 and LIG-1300~~.~~here are rather small changes in atmospheric circulation in the northern high latitudes. The warm air above Greenland is transported by the prevailing easterlies towards Canada, Alaska, the western Arctic Ocean T above Greenland is related via the lapse rate to the reduction of the ice sheet elevation to half its present value. SAT The strong increase in . , and the Barents Sea – except when changes in albedo are considered in which case The Barents Sea and Sea of Okhotsk experience a cooling of up to –2.2°C caused by an increase in sea ice. t~~

The change in the GIS elevation leads also to a relatively strong warming in the southern high latitudes, mainly off the coast of Antarctica, with the strongest positive anomaly occurring during local winter (Fig. 3a) that coincides with a heat flux transfer anomaly from the ocean to the atmosphere (not shown). Increased ocean heat flux during winter leads to a warming of the atmosphere. The Antarctic warming is most likely related to warmer deep water as well as subsurface warming poleward of 50°N in the North and South Atlantic Ocean.~~ This is an interesting feature to be studied further, but is beyond the scope of the present paper.~~ The warming may be attributed to enhanced ~~Atlantic meridional overturning circulation (~~AMOC~~,~~ (Table 2), which plays an important role in the exchange of heat between the hemispheres and between atmosphere and ocean. Our results indicate a weaker AMOC during the LIG as compared to the PI of up to 3.5 Sv, but changes in GIS lead to an increase of up to 2.2 Sv. The simulated increase in AMOC in the sensitivity simulations may be triggered by increased salinity of up to + 1 psu in the northern North Atlantic Ocean. Increased salinity cannot be explained by changes in precipitation minus evaporation, which show positive anomalies in this area (not shown). Another contributing factor to the enhanced AMOC may be an increase in the atmospheric flow due to a reduction in GIS elevation. The low pressure system over Greenland and the high pressure system above Europe become more extreme~~)S18 (Fig.~~ , enhancing the north-eastward air circulation (Fig. 11). We find that the higher the sea level pressure (SLP) anomaly, the stronger the AMOC (Table 2, Fig. ~~18S~~11). This change could also explain the positive ~~SAT~~TS anomalies of up to +1°C in the northern North Atlantic Ocean, with more heat being transported poleward from the low latitudes (Fig. 2a–c). However, convection cannot be the only explanation for the southern high latitudes warmth, since the heat would be dispersed towards the Southern Hemisphere. We however note a large scale warming in the subsurface of the Southern Ocean which is probably caused by positive feedbacks. This warming may be related to changes in the water stratification. We observe an invigorated vertical mixing in the northern North Atlantic Ocean and a suppressed vertical mixing in the Southern Ocean (not shown), the latter causing the heat at subsurface to be preserved. The Southern Ocean has a large heat capacity leading to a long memory of the system. Lags of up the three months occur in the surface layer including sea ice (amplifying factor via positive ice-albedo and ice-insulation feedbacks), while long-term lags occur in deeper levels below the summer mixed layer that store seasonal thermal anomalies (Renssen et al., 2005).

In contrast to our results that show an increase in the AMOC relative to GIS elevation changes, Otto-Bliesner et al. (2006) and Bakker et al. (2012) find a weakening of the AMOC. Bakker et al. (2012) infer that the AMOC is weaker by up to 14 % in a regional study of LIG climate of the North Atlantic Ocean, prescribing a reduction of GIS elevation (by 700 m) and extent (reducing the ice volume by 30 %). The weakening of the AMOC is caused by additional freshwater runoff resulting from a melting GIS, a factor that is not considered in our study and that would probably cancel out or reduce the effect of changes in the atmospheric transport on the AMOC. In the study by Bakker et al. (2012), reducing

GIS elevation and extent leads to changes in the atmospheric flow pattern and creates a special pattern of surface pressure anomalies. In particular in the Norwegian Sea, Barents Sea, and south-east of Greenland, the low pressure system is weaker inhibiting the overturning circulation.

The reduction of the GIS elevation and albedo alone leads in the study by Bakker et al. (2012) to a local warming of up to +4°C in July, a substantially lower anomaly (factor of ∼3) than simulated in our model for local summer when reducing both GIS and albedo. However, when comparing their simulated data to proxy-based temperature anomalies relative to PI (CAPE Last Interglacial Project Members, 2006), Bakker et al. (2012) find an overestimation of the temperature reconstruction over Greenland, and an underestimation at eastern Europe and Baffin Island – locations where we find a similar temperature tendency (Fig. 6~~8~~a).

Another climate model study that considers a reduction in GIS topography by various methods has been performed by Merz et al. (2014). In their GIS sensitivity simulations, performed with the Community Climate System Model (version 4, CCSM4), they find a rather mixed signal in temperature anomalies over Greenland relative to the predominant warming found in our simulations with changes in GIS. During local winter, their model simulates a warming of up to +5°C in central Greenland and a cooling of up to -12°C in areas that become flat and ice-free. However, changes in topography of GIS do not have a significant influence on climate in the surrounding areas in the study by Merz et al. (2014). This may be caused by the fact that in their simulations SSTs are prescribed, while in our study the atmosphere model is interactively coupled to an ocean general circulation model. However, in their study the GIS is reconstructed by means of high resolution ice sheet models, while we consider a relatively simplistic representation of the GIS. Differences are found also with respect to changes in low-level winds. They find a rather local influence of the GIS changes and no major effect on the large-scale atmospheric circulation. Our model simulates an enhancement of low-level winds around GIS and on SLP (Fig. 11). As such, the methods of reducing GIS and the model used have a strong influence on the local and large-scale climate. Note, however, that the aims of our study and the study by Merz et al. (2014) are different, since the latter focuses on local effects above Greenland, while our main focus is on the GIS effects on large-scale climate.

In each early LIG simulation that simulates a reduced GIS, we observe a cooling in the west of Greenland of up to −2°C. This cooling may be connected to an increase in sea ice south-west of Greenland (not shown). Furthermore, the atmospheric circulation is affected by the reduction of GIS elevation, transporting more cold air from the Arctic into the Baffin Bay (Fig. ~~S~~11~~8~~). A local cooling at this region is found also by Dethloff et al. (2004), who performed a regional model study in which the GIS is completely deglaciated, but global sea surface temperatures (SSTs) are fixed. They find that a deglaciated GIS causes a cooling in the west and south of Greenland of up to −6°C and a maximum warming over Greenland of up to +9°C. Dethloff et al. (2004) propose that these changes over Greenland are linked to elevation changes and a shift in the cyclonic storm tracks.

4.2~~3~~ Surface ~~air~~ temperature evolution during the Last Interglacial and the Holocene

~~Vegetation-climate feedback may have a strong influence on temperatures, leading to a warming in the northern high latitudes (Crucifix et al., 2002; Schurgers et al., 2007). throughout the simulation. This effect may be caused by the vegetation feedback, which is dynamic in the control simulation.SATsions of the GHGs (as proposed by PMIP3, Table 2) compared to the LIG control simulation (LIG-ctl-tr), it reproduces higher m-alb-tr and LIG-×0.5-tr reproduce similar magnitudes (Fig. 6). Although the LIG-GHG-tr simulation considers lower concentrat m-alb-tr) – particularly in the northern high latitudes, where albedo has the strongest impact (Fig. 5). In middle latitudes, simulations LIG-1300 being simulated in the simulation with reduced GIS (1300 m) and adjusted albedo (LIG-1300SATs magnitudes, with the highest SATWe choose these latitudinal bands due to the differing insolation. All transient LIG simulations reproduce similar trends, but different absolute : high latitudes (60–90°N, Fig. 5), middle latitudes (30–60°N, Fig. 6), and low latitudes (0–30°N, Fig. 7). NH evolution (annual mean, local summer, and local winter) in three latitudinal bands of the SAT changes during the LIG and the Holocene, we conduct an intercomparison of transient climate evolution under different interglacial background conditions. To this end, we analyze simulated transient LIG (130–115 kyr BP) and Holocene (8–0 kyr BP) SAT~~

~~In order to investigate the spatio-temporal behaviour of~~ Although our results are not directly comparable to those derived by Bakker et al. (2013), who analyze transient LIG January and July temperature anomalies (simulated by seven different models) with respect to PI while we use transient absolute ~~SAT~~TS~~s~~ for coldest and warmest month, the pattern of the temperature evolution remains the same. We observe similarities in middle latitudes and in winter temperatures at high latitudes characterized by a large variability, and also note a clear cooling trend for summer caused by a decrease in summer insolation. At northern high latitudes, Bakker et al. (2013) find July maximum LIG warmth at 128.4–125.1 kyr BP, while in middle latitudes the maximum occurs at 129.4–126.3 kyr BP. We also observe a warmest month maximum at around 128 kyr BP for high and middle latitudes. A July maximum LIG warmth is found in the study by Loutre et al. (2014) at 128 kyr BP. They find that the summer SST during the LIG is smaller in the model than in the reconstructed temperatures, especially in the North Atlantic Ocean, but taking into account the evolution of the Northern Hemisphere ice sheets reduces the disagreement between model and data.

During winter, our simulations produce a clear high latitude ~~SAT~~TS maximum around mid-LIG, while the middle latitudes experience peak warmth around 121–117 kyr BP. Bakker et al. (2014) compare transient LIG and Holocene (8–0 kyr BP) temperature trends simulated by different models (including our COSMOS LIG-GHG-tr and HOL-tr simulations). They find negative warmest month temperature trends for both LIG and Holocene in the ~~NH~~Northern Hemisphere, and they propose that the climate reacts linearly to changes in insolation. Bakker et al. (2013) find a linear relation between changes in insolation and temperatures for both summer and winter and for all latitudes. There are however some exceptions. In northern high-latitudes, the winter temperature changes result mainly from sea-ice related feedbacks and are described as highly model-dependent. In southern middle to high latitudes, winter temperatures are strongly affected by changes in GHG concentrations. Comparing all LIG transient simulations with the Holocene in the three considered latitudinal bands, we observe that the Holocene experiences mostly lower ~~SAT~~TS than during the LIG, and is characterized by smaller trends.

In our LIG transient simulations, we find that the differences in ~~SAT~~TS between the different model simulations at the beginning of the LIG (130 kyr BP) are higher than during the late LIG (115 kyr BP), indicating that the impact of a reduced GIS is stronger at the beginning of the LIG as compared to glacial inception (GI, 115 kyr BP). By using different approaches to simulate the LIG evolution, we offer a bandwidth of possible temperatures at each given time.

44.3 Model-data comparison

In combination with changes in the GIS elevation and lower albedo, the insolation effect causes strong positive ~~SAT~~TS anomalies in the ~~NH~~Northern Hemisphere, especially during summer (Figs. 4c~~C~~ and 6~~8~~a). The pattern of these changes is observed also in a model study of the LIG that includes changes in GIS elevation of 500 m (Otto-Bliesner et al., 2006). The study shows that the June-July-August (JJA) temperature anomaly with respect to PI is positive in the ~~NH~~Northern Hemisphere especially over the continents – yet, the magnitude of these changes is smaller than in our study. The Barents Sea experiences no temperature change in Otto-Bliesner et al. (2006), compared to a warming of +2 to +4°C simulated by our model. The only location in simulations by Otto-Bliesner et al. (2006) that is notably warmer than in our simulations is at the western side of Greenland – the high decrease in GIS elevation prescribed in our simulation is accompanied by modest ~~SAT~~TS anomalies at the western side of Greenland, which may be related to an increase in the sea ice. In order to validate their results, Otto-Bliesner et al. (2006) compare the simulated temperature anomalies to proxy-based temperature anomalies by CAPE Last Interglacial Project Members (2006), the same temperature reconstruction data that we use in our model-data comparison (Figs. 6~~8~~, 8~~10~~a, S4a~~6~~, S5~~8a~~, S6~~9~~, and S10~~, and S15~~). Comparing our model results with the marine and terrestrial reconstruction temperatures by CAPE Last Interglacial Project Members (2006), we see most similarities with respect to temperature in the summer anomalies of LIG relative to PI, although at some locations the magnitude differs. At the western side of Greenland, our model underestimates the terrestrial proxy-based temperature anomalies by at least 2°C, while in Alaska there is an overestimation, making the model-data agreement of Otto-Bliesner et al. (2006) better. Over Greenland, the warming reaches +5°C according to the proxy reconstructions, while our results show a higher warming caused by the reduction of the GIS. ~~CAPE Last Interglacial Project Members (2006) suggest that positive feedbacks from the intensification of the North Atlantic Drift that bring warm water from the Gulf Stream poleward contributed to the 5°C warming of the Arctic. The albedo also played a role in the warming as a result of sea ice reduction and the extension of forest in the Arctic (CAPE Last Interglacial Project Members, 2006).~~

~~-~~Over Greenland, the model overestimates the proxy-based temperature anomalies, while the results from Otto-Bliesner et al. (2006) indicate an underestimation. This suggests that the GIS elevation during the LIG may have not been so drastically reduced as prescribed in our model setup, but was still reduced by at least 500 m. This conclusion is supported also by another study (Stone et al., 2013) that compares simulated LIG ~~SAT~~TS anomalies relative to PI to anomalies derived from the reconstruction by CAPE Last Interglacial Project Members (2006). In their simulation, which was produced using the coupled atmosphere–ocean general circulation model HadCM3 (Hadley Centre Coupled Model, version 3), Stone et al. (2013) find a good agreement between model and reconstruction as well, but cannot capture the reconstructed strong warming over Greenland, their simulation indicating a warming of up to +3.5°C. They imply that the GIS was reduced in the LIG as compared to PI, but not completely deglaciated – in the simulation with a completely removed GIS, they find much stronger temperature anomalies over Greenland of up to +16°C, higher than in our findings when GIS is reduced to half its present elevation (Fig. 2).

Proxy records based on ice cores indicate over Greenland positive summer anomalies of up to +5°C at the maximum LIG warmth (Johnsen et al., 2001; NGRIP members, 2004). The corresponding simulated temperature anomalies at Renland ice core site (Johnsen et al., 2001) are +4.93°C in the LIG-ctl simulation and +8.71°C in the LIG-1300m-alb simulation, indicating that in eastern Greenland, the height of the ice sheet was probably similar to preindustrial elevation. An overestimation by the model occurs at NGRIP ice core location (NGRIP members, 2004), whether changes in GIS are taken into account or not, the LIG-ctl and LIG-1300m-alb simulations indicating a warming of +7.46°C and of +11.13°C, respectively. A warming as high as +8 ± 4°C is proposed by Dahl-Jensen et al. (2013) for the peak LIG warmth at 126 kyr BP, based on North Greenland Eemian Ice Drilling (NEEM) ice core. They propose that the northwest GIS is characterized only by a modest reduction of 400 ± 250 m between 128 and 122 kyr BP. In our study, we find at the location of the NEEM ice core an annual mean warming of +9.6°C at 125 kyr BP at a GIS height of 553 m. Antarctic ice cores indicate positive temperature anomalies of up to +3.5°C (Capron et al., 2014), overestimating the simulated TS. However, a reduction in GIS reduces the model-data disagreement.

In order to determine whether a lowered GIS creates a better agreement with the data, we compare the proxy records derived by CAPE Last Interglacial Project Members (2006) to simulation LIG-ctl (Figs. ~~S~~6c~~a~~ and S4~~8~~a). We find a better agreement for some records, especially over Greenland where the warming in the simulation LIG-ctl is of a lower magnitude. A high overestimation of reconstructed temperatures by the model is found also by Otto-Bliesner et al. (2006) for a deglaciated Greenland, with summer temperature anomalies being higher than +10°C. Although in our simulations we do not completely remove the ice sheet, we find strong ~~SAT~~TS anomalies of up to +11°C. The Siberia region experienced similar anomalies in the reconstruction, with records showing +4 to +8°C warming, slightly overestimating our model results. ~~A few records that are located in Asia indicate a better agreement with our model results than with simulated temperatures by Otto-Bliesner et al. (2006).~~ The Arctic Ocean and the North Atlantic Ocean show, in both Otto-Bliesner et al. (2006) and this publication, only modest changes in temperature, mostly underestimating the marine data. The discrepancy is partly removed by considering ~~modelled~~simulated ~~SAT~~TS anomalies for maximum summer warmth during the LIG (Fig. 6d~~8b~~).

We go one step further and perform an additional model–data comparison with global coverage (Turney and Jones, 2010). Lunt et al. (2013) performed a model–data comparison for the LIG, using a multi-model approach including our LIG-GHG simulation. None of the model simulations, used in their study, consider a reduction of the GIS elevation or albedo. As in our simulations, Lunt et al.

(2013) find that the models fail to capture the magnitude of the temperature anomaly suggested by the proxy data. In their study, the model–data difference is slightly higher than in our study when comparing simulations to terrestrial data, as none of the simulations manage to capture a strong annual mean warming in the high latitudes. In fact, most of the models suggest a slight cooling over northern Asia at the beginning of the LIG (130 kyr BP) and only a slight warming over Greenland. Over Alaska, the proxy records show a strong warming, which is not captured by any simulation analyzed by Lunt et al. (2013). Our reduced GIS simulation (LIG-1300-m-alb) also presents as well a warming, but of a slightly higher magnitude, reducing the disagreement between model and data. Most of the temperature records in Europe indicate a positive LIG temperature anomaly, whereas the multi-model analysis by Lunt et al. (2013) captures mostly a slight cooling. Another region where reconstructions agree better with our modelledsimulated SATTS is situated over Antarctica, where modelledsimulated and reconstructed temperature anomalies indicate a warming of similar magnitude, in contrast to the simulations performed by Lunt et al. (2013), where most of the models indicate a slight cooling. These results imply that a reduced GIS during the LIG may have contributed to an increase in temperature – in our study, the difference between the terrestrial proxy-based temperature anomalies and the anomalies of LIG simulation that implies a PI GIS configuration is higher than when reduced GIS is considered (Figs. 79 and S7). The RMSD values support this assumption (Table 2), although differences between the considered cases (i.e. with or without a reduction in GIS) are relatively small. The differences are small because in the calculation of the RMSD, all the proxy records by Turney and Jones (2010) are considered, including a large number of records in the low latitudes where a change in GIS has no influence. Yet, in all simulations the models do not capture the magnitude of the SST anomalies derived from marine records. Such underestimation of proxy data by the models is also found in model–data comparison studies for the Holocene (Masson-Delmotte et al., 2006; Brewer et al., 2007; Sundqvist et al., 2010; Zhang et al., 2010; O'ishi and Abe-Ouchi, 2011; Braconnot et al., 2012; Lohmann et al., 2013; Bakker et al., 2014). Lohmann et al. (2013) show that the modelledsimulated SST trends systematically underestimate the marine proxy-based temperature trends, and suggest that such discrepancies can be caused either by too simplistic interpretations of the proxy data (including dating uncertainties and seasonal biases) or by underestimated long-term feedbacks in climate models, a feature which is probably also valid for the LIG. Such long-term feedbacks missing in our model is for example the lithosphere which has not been yet implemented in COSMOS. A coupled ice sheet model and biogeochemistry are already implemented in the COSMOS but are relatively new tools. We did not consider them in our simulations because running the carbon cycle and the ice sheet into equilibrium would take a very long computational time. Additionally, other factors like glacial memory effect is not well represented and cannot be fully reproduced by the models.

Our reduced GIS simulation (LIG-1300-m-alb) indicates a strong annual mean warming in the high latitudes with respect to PI (Fig. 7~~9~~a). These changes are in accordance with the terrestrial proxy-based temperature anomalies by Turney and Jones (2010), although at northern high latitudes the order of magnitude differs between model and reconstruction, with the model underestimating the reconstructions. The ocean surface in the middle and low latitudes experiences mostly no ~~SAT~~TS change in our simulation, in contrast to the proxy-based SST anomalies that indicate strong positive or negative temperature changes. Our results partly contradict another early LIG (130 kyr BP) model simulation study performed by Otto-Bliesner et al. (2013). The Community Climate System Model 3 (CCSM3) used in their analysis simulates mostly a cooling in the ocean, with the exception of the North Atlantic Ocean south of Greenland, where the anomalies have the same sign as proxy-based SSTs by Turney and Jones (2010). Terrestrial proxy-based temperatures indicate a better agreement with our simulation, especially over northern Asia, Alaska, and Antarctica. Even when considering mid-LIG (125 kyr BP), in both studies (see Figs. S11~~ and S176~~ for our study), the terrestrial data can be better reconciled with the simulation in which GIS elevation and albedo are reduced, especially over Antarctica where Otto-Bliesner et al. (2013) find a cooling. Nevertheless, the difference between the magnitude of change in model and reconstruction is still large. One contributing factor to warmer temperatures in the high latitudes in our study may be (as also proposed by Otto-Bliesner et al., 2013) the vegetation feedback, which is considered in our simulations. Over Greenland, the CCSM3 model underestimates the ice record data, while our model simulations LIG-×0.5, LIG-1300-m, and LIG-1300-m-alb capture an overestimation. Otto-Bliesner et al. (2013) propose that the Greenland ice records may capture temperatures associated with a reduction in GIS elevation. This suggests again that the LIG GIS was lower, but possibly not as low as prescribed in our study. Otto-Bliesner et al. (2013) take into account also possible seasonal biases considered by Lohmann et al. (2013). To this end, they compare the proxy data to simulated JJA temperature anomalies for which they find the best fit, suggesting that the proxies record boreal summer temperatures. In our study, we find the best overall fit for simulated annual mean rather than summer ~~SAT~~TS~~s~~ (Figs. S11a and S12a) in all three cases: reduced GIS and albedo for beginning of the LIG (LIG-1300-m-alb, 130 kyr BP, Figs. 7~~9~~a and 8~~10~~b), for mid-LIG (LIG-125k, 125 kyr BP, Figs. S11~~6~~a, c~~ and S17a~~), and for the control run with prescribed

PI GIS (LIG-ctl, 130 kyr BP, Figs. 6c~~S7a~~ and S4~~8~~b), with the best agreement between model and data in the first case (Table S2). This could indicate that the proxies may indeed record annual mean temperatures, but in a warmer climate caused by a reduced GIS (Fig. 7~~9~~a). While the simulated summer ~~SAT~~TS~~s~~ are closer to the proxies at some locations (e.g. Northern Asia and Europe, Fig. S7~~11~~a), there are still more records that agree best with the simulated annual mean ~~SAT~~TS~~s~~ (Fig. 7~~9~~a). Otto-Bliesner et al. (2013) include in their study also a mid-LIG simulation performed by Gordon et al. (2000) with the HadCM3 model. Their simulation indicates an even lower agreement between model and data. ~~When comparing our COSMOS model simulations with those from Lunt et al. (2013) and Otto-Bliesner et al. (2006, 2013), COSMOS performs comparably well, with respect to reconstructed data (CAPE Last Interglacial Project Members, 2006; Turney and Jones, 2010).~~

4.4~~5~~ Limitations of model-data comparison

One challenge in an effective LIG model–data comparison is the difficulty to determine an absolute dating of LIG marine paleo-proxy records (e.g. Drysdale et al., 2009), as few techniques exist for this purpose. The dating of most of the records is derived by lining up the climatic signal recorded in sediment cores to the SPECMAP (SPECtral MAping Project, Imbrie et al., 1984; Martinson et al., 1987) reference curve, which is tuned to the June insolation at 65°N. This strategy allows a relative dating of sediment cores through global effects of glacial–interglacial climate changes beyond the time limit of radiocarbon dating (Fairbanks et al., 2005; Chiu et al., 2007; Reimer et al., 2009; Shanahan et al., 2012; Reimer et al., 2013), but it may lead to an artificial synchronization of all records and therefore dampen regional differences in climate records with respect to the LIG chronozone. A relatively new method for synchronizing different types of proxies from different regions is used in Capron et al. (2014). They align proxy records to the AICC2012 ice core chronology allowing for consideration of dating uncertainties. Their study shows that the maximum temperature changes during the LIG is different between the two hemispheres, the records from Southern Ocean and Antarctica showing an early maximum compared to the records from northern high latitudes.

Additionally, some proxy records that are considered as recording annual mean temperatures are seasonally biased, depending on the type of the proxy or on the region (Leduc et al., 2010; Schneider et al., 2010; Lohmann et al., 2013). Furthermore, ~~One challenge in an effective LIG model–data comparison is the uncertainty in~~ defining the timing of the maximum warmth during the LIG represents as well a challenge. Different studies (model- as well as proxy-based) suggest that the maximum warmth occurred at different times throughout the LIG with regional dependency (Bakker et al., 2012;

Govin et al., 2012; Langebroek and Nisancioglu, 2014). A study that involves transient LIG simulations performed with nine different models is presented by Bakker and Renssen (2014), who find that the calculation of the maximum LIG temperature is largely model-dependent, and also shows geographical- and time-dependency (retrieved values differ between the annual mean and warmest month temperature anomalies). Bakker and Renssen (2014) propose that the time-dependency originates from the dependency of the time evolution of orbital forcing on latitude and seasons, as well as from the thermal inertia of the oceans and from different 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. Our model results indicate that the timing of maximum LIG warmth is indeed regionally dependent (Fig. 9~~11~~). ~~anomalies to the proxy-based temperature anomalies.SAT~~

~~Another limitation is the difficulty to determine an absolute dating of LIG marine paleo-proxy records (e.g. Drysdale et al., 2009), as few techniques exist for this purpose. The dating of most of the records is derived by lining up the climatic signal recorded in sediment cores to the SPECMAP (SPECtral MAping Project, Imbrie et al., 1984; Martinson et al., 1987) reference curve, which is tuned to the June insolation at 65°N. This strategy allows a relative dating of sediment cores through global effects of glacial–interglacial climate changes beyond the time limit of radiocarbon dating (Fairbanks et al., 2005; Chiu et al., 2007; Reimer et al., 2009; Shanahan et al., 2012; Reimer et al., 2013), but it may lead to an artificial synchronization of all records and therefore dampen regional differences in climate records with respect to the LIG chronozone. Additionally, some proxy records that are considered as recording annual mean temperatures are seasonally biased, depending on the type of the proxy or on the region (Leduc et al., 2010; Schneider et al., 2010; Lohmann et al., 2013). To overcome this problem, we compare simulated annual mean (Figs. 9, 10b, c, S7, S8b, c, S8b, S10, S15a, c, S16a, and S17a) and warmest month mean (Figs. 8, 10a, S6, S8a, S11, S12, S13, S15b, d, S16b, and S17b) SAT anomalies to the proxy-based temperature anomalies.~~

~~4.6 Partial reduction of model-data mismatch~~

~~Taking into account the uncertainties in defining the timing of the maximum LIG warmth and the seasonal biases, we are able to partly reconcile model–data discord. In Alaska, the terrestrial proxy-based temperature anomalies derived by CAPE Last Interglacial Project Members (2006) fit very well to the modelled SAT anomalies when we consider maximum annual mean SATs in LIG-ctl-tr (Fig. S9d), which may imply that these specific records may represent in fact annual mean temperatures~~

~~rather than a summer signal. At south-west of Greenland, the best agreement is found for the comparison with maximum summer LIG warmth for both simulations LIG-1300 m-alb-tr and LIG-ctl-tr, although no simulation captures the magnitude of change recorded by the data (Figs. 8b and S6b). Over Greenland, modelled annual mean SAT in simulation LIG-ctl at 130 kyr BP and at maximum LIG warmth underestimates the proxy data by ~3°C (Fig. S9b, d), while in simulation LIG-1300 m-alb there is an overestimation of proxy data in all considered cases (Figs. 8 and 9a, c). For northern Asia, the best model–data agreement is found in simulation LIG-1300m-alb-tr for maximum summer LIG warmth (Fig. 8b). For the Turney and Jones (2010) terrestrial proxy dataset, agreement with the simulation for northern high latitudes is best during maximum summer LIG warmth in simulation LIG-1300 m-alb-tr (Fig. S11b). Similar inferences are derived for Europe, except for proxy records that indicate a negative temperature anomaly, in which case the fit is best with annual mean SATs at 130 kyr BP in simulation LIG-ctl (Fig. S7a), although none of the considered cases indicate a cooling in that area. Over Antarctica, the best model–data agreement is found for annual mean in simulation LIG-1300 m-alb at 130 kyr BP (Fig. 9a). For the marine records in the northern North Atlantic Ocean, the closest fit is derived during summer at maximum LIG warmth in simulation LIG-1300 m-alb-tr (Fig. S11b), although the records are considered to represent annual mean temperatures at the $\delta^{18}O$ plateau. The low latitudes experience strongest cooling in simulation LIG-ctl during summer at 130 kyr BP, but the magnitude of change is still much smaller than recorded by proxy. These results indicate that, in dependency of location and under distinct GIS boundary conditions, different proxies may record different seasons and timing of the maximum warmth within the LIG.~~

~~To partly resolve the timing uncertainty, we additionally calculate the maximum and minimum LIG SAT derived from our LIG transient simulation (LIG-1300 m-alb-tr) for each core location, providing the possibility of a better agreement between model and data and partially removing the model–data mismatch (Figs. 8b, 9b, and 10). Globally, the terrestrial records show an agreement with the model in 19 to 33 % of the cases, while the marine records are only equivalent to the simulation in 12 to 15 % of the cases. Seasonality provides the possibility of reconciling 51 to 69 % of the terrestrial records and 31 to 33 % of the marine records to the corresponding simulated temperature data.~~

5. Conclusions

In this study, we have analyzed data from several LIG sensitivity simulations performed with an atmosphere–ocean general circulation model~~,~~ and assess the influence of the GIS on global climate~~with a focus on a reduction of the GIS elevation. We employed different approaches in order to assess the~~

~~influence of the GIS on the global climate~~. We have compared the simulated ~~SAT~~TS changes to anomalies as recorded by proxy reconstructions by CAPE Last Interglacial Project Members (2006), ~~and~~ Turney and Jones (2010), and a compilation of synchronized records by (Capron et al., 2014).

We have shown that the exact method by which GIS configuration is changed has a significant influence on hemispheric temperature anomalies. A reduc~~ed~~tion in GIS by ~1300 m and changes in albedo (LIG-1300m-alb simulation) enhance~~s~~ the warming caused by changes in the astronomical forcing by up to +5°C~~m-alb) LIG-1300simulation , with the strongest influence being simulated when a reduction of both elevation and extent of the GIS is considered (~~. The LIG is much warmer than the PI, especially during summer in the ~~NH~~Northern Hemisphere and during winter in the ~~SH~~Southern Hemisphere and in the northern high latitudes. ~~Middle to high latitudes are cooler during LIG winter.~~ The astronomical forcing influence is dominant (relative to changes in GIS) in the global and Northern Hemisphere average of annual mean and local summer TS, and in the Southern Hemisphere winter. Changes in GIS have the strongest influence (relative to insolation changes) globally and in the Northern Hemisphere winter average TS, and in the Southern Hemisphere summer.~~These changes are predominantly caused by an increase in insolation, followed by the effect of a lowered GIS and subsequent changes in albedo.~~

Modification of the GIS alone leads to a warming mostly in the northern and southern high latitudes. Cooling occurs locally in Barents Sea or Sea of Okhotsk (depending on the simulation). The warming caused by a reduced GIS has a winter signal, rather than a summer signal at both hemispheres. Winter ~~SAT~~TS over the Arctic Ocean is warmer by up to +3°C due to GIS changes, with an additional warming of +1 to +2°C caused by winter insolation changes, relative to PI.

The simulated ~~SAT~~TS~~s~~ underestimate the temperature changes indicated by the proxy reconstructions. However, ~~A~~a reduction in GIS elevation and extent improves the agreement between model and data by Turney and Jones (2006). For terrestrial records, which represent annual mean temperature anomalies at maximum LIG warmth, the best agreement is found for annual mean TS anomalies at maximum LIG warmth derived from the simulation with changes in GIS and albedo (LIG-1300m-alb-tr simulation). This result is in contrast to other model studies that find a best agreement when summer averages are considered ~~Nevertheless, a~~At low latitudes the model does not capture the pronounced changes indicated by the marine proxies derived by Turney and Jones (2010). Most of the records derived by CAPE Last Interglacial Project Members (2006) and Capron et al. (2014) agree best with the model simulation that considers a preindustrial~~PI~~ GIS configuration, because changes in GIS have the strongest influence during winter and the respective datasets represent summer temperatures~~.~~

Throughout the LIG, winter in the northern high latitudes is characterized by high temporal variability, while summer ~~SAT~~TS~~ in the middle to high latitudess~~ indicate a clear cooling trend. ~~latitudinal bands, the Holocene is predominantly cooler than the LIG.NH In all change during the LIG.SAT Low latitudes experience only a modest~~ By considering transient simulations with different boundary conditions (i.e. GIS elevation, albedo, insolation, GHG concentrations) we offer a bandwidth of potential temperatures at each given time throughout the LIG, between 130 and 115 kyr BP. We reduce the mismatch between model and data by additionally considering uncertainties in absolute dating of the proxy reconstructions~~, their possible seasonal biases~~, and uncertainties in the timing of maximum LIG warmth (calculated in our study as the ~~modelled~~simulated maximum LIG warmth between 130 and 120 kyr BP at each given location). The definition of maximum interglacial warmth provides therefore an additional uncertainty and the LIG does not provide a strong constrain for estimating the amplitude of interglacial climate change~~sensitivity~~. Future studies that provide a better multi-proxy interpretation and a better representation of the climate models are needed in order to reduce the model–data mismatch. Our sensitivity simulations represent a starting point for future studies on transient integrations of the LIG climate that include also transient changes in GIS elevation and extent, and for the comparison of such results to high-quality proxy data. More climate model sensitivity studies on the effects of a reduced GIS on global climate are needed in order to understand the response of different models to such changes, as the ability of the models to properly simulate future states of the GIS is critical.

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Table and Figure captions

Table 1. Overview of model configuration and climate forcings for the COSMOS simulations presented in this study. PI = preindustrial, Veg. = vegetation; dyn. = dynamic; e = eccentricity; ε = obliquity; ω = length of perihelion. The Greenland Ice Sheet (GIS) configuration is, in dependence of the simulation, as follows: PI – ~~PI~~preindustrial GIS elevation and~~ PI~~ land ice mask; ×0.5 – ~~PI~~preindustrial GIS elevation multiplied by 0.5 (at every grid point over Greenland) and ~~PI~~preindustrial land ice mask; −1300 m – ~~PI~~preindustrial GIS elevation minus 1300 m (at every grid point over Greenland; where ~~PI~~preindustrial elevation is below 1300 m, the land is set to 0 m) and ~~PI~~preindustrial land ice mask; −1300 m+alb – ~~PI~~preindustrial GIS elevation minus 1300 m (at every grid point over Greenland; where ~~PI~~preindustrial elevation is below 1300 m, the land is set to 0 m and albedo adjusted accordingly) and adjusted land ice mask. The different GIS configurations are displayed in Fig. 1. * Simulations that are presented in the supplementary material.

Table 2. Atlantic Meridional Overturning Circulation (AMOC) and absolute values of surface~~ air~~ temperature (~~SA~~TS) for global, Northern Hemisphere (NH), and Southern Hemisphere (SH) coverage, calculated for annual mean, local summer mean (warmest month), and local winter mean (coldest month).

Figure 1. Greenland Ice Sheet (GIS) elevation (in m) and land ice cover prescribed in our COSMOS model simulations: **(a)** preindustrial~~ (PI)~~ GIS and~~ PI~~ land ice mask, **(b)** ×0.5 GIS and ~~PI~~preindustrial land ice mask, **(c)** −1300 m GIS and preindustrial~~PI~~ land ice mask, **(d)** −1300 m and adjusted land ice mask. In **(a)**, the ~~PI~~preindustrial elevation and land ice mask are unchanged. In **(b)**, the preindustrial~~PI~~ elevation over the GIS area is multiplied by 0.5; the land ice mask is unchanged. In **(c)**, for each grid point over the GIS, 1300 m are subtracted from ~~PI~~preindustrial elevation; the land ice mask is unchanged. In **(d)**, for each grid point over the GIS, 1300 m are subtracted from preindustrial~~PI~~ elevation; at grid locations where the elevation is lower than 1300 m, land ice is removed and albedo is adjusted accordingly.

Figure 2. Effect of **(a–c)** Greenland Ice Sheet elevation and **(c, d)** albedo ~~at the beginning of the Last Interglacial (~~in the 130 kyr BP simulations~~)~~. Annual mean surface ~~air~~ temperature~~ (SAT)~~ (TS)

anomalies (in °C) for simulations: **(a)** LIG-×0.5 minus LIG-ctl, **(b)** LIG-1300-m minus LIG-ctl, **(c)** LIG-1300-m-alb minus LIG-ctl, and **(d)** LIG-1300-m-alb minus LIG-1300-m. Hatched areas mark statistically insignificant ~~SAT~~ TS anomalies.

Figure 3. Effect of Greenland Ice Sheet elevation and albedo ~~at the beginning of the Last Interglacial (~~on surface temperature in the 130 kyr BP simulation (LIG-1300m-alb simulation~~)~~. Same as Fig. 2c but for: **(a)** local winter mean (coldest month) and **(b)** local summer mean (warmest month). Violet dashed lines represent the LIG-1300-m-alb 50 %-compactness sea ice isoline, violet continuous lines represent the LIG-1300-m-alb sea ice edge. Green dashed lines represent the LIG-ctl 50 %-compactness sea ice isoline, green continuous lines represent the LIG-ctl sea ice edge.

Figure 4. Effect of Greenland Ice Sheet elevation, insolation, and albedo ~~at the beginning of the Last Interglacial (LIG,~~at 130 kyr BP~~)~~ relative to preindustrial (PI). Surface~~ air~~ temperature (~~SA~~TS) anomalies (in ° C) between the Last Interglacial~~LIG~~ (LIG, LIG-1300-m-alb-CH_4 simulation) and PI (PI simulation) for: **(a)** annual mean, **(b)** local winter mean (coldest month), and **(c)** local summer mean (warmest month). Violet dashed lines represent the LIG 50 %-compactness sea ice isoline, violet continuous lines represent the LIG sea ice edge. Green dashed lines represent the PI 50 %-compactness sea ice isoline, green continuous lines represent the PI sea ice edge. Hatched areas mark statistically insignificant ~~SAT~~TS anomalies.

Figure 5. Simulated surface~~ air~~ temperature evolution (in °C) for the Last Interglacial (LIG, 130–115 kyr BP, LIG-ctl-tr, LIG-×0.5-tr, LIG-1300-m-alb-tr, and LIG-GHG-tr simulations) and the Holocene (8–0 kyr BP, HOL-tr simulation) in northern high latitudes (60–90°N) calculated as running average with a window length of 21 model years representing 210 calendar years for: **(a)** annual mean, **(b)** local winter mean (coldest month), and **(c)** local summer mean (warmest month). The lower *x* scale represents the LIG time scale, the upper *x* scale indicates the Holocene time scale. The upper *x* scale is matched to the time scale between 128 and 120 kyr BP, as Drysdale et al. (2009) propose that Termination I and Termination II are similar with respect to obliquity.

~~**Figure 6.** Same as Fig. 5 but for northern middle latitudes (30–60°N).~~

Figure 7. Same as Fig. 5 but for northern low latitudes (0–30°N).

Figure 86. Effect of **(a, b)** Greenland Ice Sheet elevation, insolation, albedo, and atmospheric methane concentration and **(c, d)** insolation and atmospheric methane concentration for the Last Interglacial (LIG) relative to preindustrial (PI). Model-data comparison of mean local summer temperature anomalies (in °C). The shading represents the simulated surface air temperature (SATS) anomalies at the **(a, c)** beginning of the LIG (130 kyr BP, derived from **(a)** LIG- 1300 m-alb simulation) and **(c)** LIG-ctl simulation, and **(b, d)** summer maximum LIG warmth (warmest 100 warmest months between 130 and 120 kyr BP) derived from **(b)** LIG-1300m-alb-tr simulation and **(d)** LIG-ctl-tr), relative to PI. Hatched areas in **(a, c)** mark statistically insignificant SATTS anomalies. The squares and circles show marine and terrestrial proxy-based maximum LIG summer temperature anomalies relative to PI derived by CAPE Last Interglacial Project Members (2006). The colors inside the squares and circles represent the proxy-based temperature anomalies derived from the intervals provided by CAPE Last Interglacial Project Members (2006), that agree best with the modelledsimulated SATTS anomalies at the location of the proxies. The $RMSD_{terrestrial}$ = 2.63°C and $RMSD_{marine}$ = 2.20°C for **(a)** and $RMSD_{terrestrial}$ = 2.54°C and $RMSD_{marine}$ = 2.26°C for **(b)**. When considering only the 5 marine records located in northern North Atlantic Ocean, $RMSD_{marine}$ =1.99°C for **(a)** and $RMSD_{marine}$ = 1.48°C for **(b)**.

Figure 97. Effect of **(a, b)** Greenland Ice Sheet elevation, insolation, albedo, and atmospheric methane concentration and **(c, d)** insolation and atmospheric methane concentration for the Last Interglacial (LIG) relative to preindustrial (PI). Model-data comparison of mean annual temperature anomalies (in °C). The shading represents the simulated surface air temperature (SATS) anomalies at the **(a, c)** beginning of the LIG (130 kyr BP, derived from **(a)** LIG-1300-m-alb simulation and **(c)** LIG-ctl simulation, and **(b, d)** maximum LIG warmth (warmest 100 model years between 130 and 120 kyr BP) derived from **(b)** LIG-1300-m-alb-tr simulation and **(d)** LIG-ctl-tr simulation, relative to PI. Hatched areas in **(a, c)** mark statistically insignificant SATTS anomalies. The squares and circles show marine and terrestrial proxy-based LIG annual mean temperature anomalies relative to present-day (1961–1990) derived by Turney and Jones (2010). The $RMSD_{terrestrial}$ = 3.23°C and $RMSD_{marine}$ = 2.52°C for **(a)** and $RMSD_{terrestrial}$ = 3.12°C for **(b)**.

Figure 108. Effect of Greenland Ice Sheet elevation, insolation, albedo, and atmospheric methane

concentration for the Last Interglacial (LIG) relative to preindustrial (PI). **(a)** Proxy-based maximum LIG summer temperature anomalies (in °C) relative to PI derived by CAPE Last Interglacial Project Members (2006) plotted against simulated local summer surface temperature (TS) anomalies at 130 kyr BP (LIG-1300m-alb simulation) relative to PI at the location of the proxies. The horizontal bars represent the proxy-based temperature intervals derived by CAPE Last Interglacial Project Members (2006). The vertical bars indicate the simulated TS anomalies at the maximum and minimum LIG TS with respect to local summer (i.e. the coldest and warmest 100 warmest months) derived from the time interval 130 to 120 kyr BP (LIG-1300m-alb-tr simulation) relative to PI, for each given proxy record location.~~, and~~ **(b)**~~, c)~~ ~~p~~Proxy-based LIG annual mean temperature anomalies relative to present-day (1961–1990) derived by Turney and Jones (2010), plotted against simulated ~~**(a) local summer and (b, c)**~~ annual mean ~~surface air temperature (SA~~TS~~)~~ anomalies at ~~the beginning of the LIG (~~130 kyr BP~~,~~ ~~(~~(LIG-1300~~-~~m-alb simulation) relative to PI at the location of the proxies. ~~The horizontal bars in **(a)** represent the proxy-based temperature intervals derived by CAPE Last Interglacial Project Members (2006).~~ The vertical bars indicate the simulated ~~SAT~~ TS anomalies at the maximum and minimum LIG TS with respect to annual mean~~SAT~~ (i.e the coldest and warmest 100 model years) derived from the time interval 130 to 120 kyr BP (LIG-1300~~-~~m-alb-tr simulation) relative to PI, for each given proxy record location.~~**, for: (a) local summer mean (i.e. the coldest and warmest 100 warmest months), (b) annual mean (i.e the coldest and warmest 100 model years), and**~~ **(c)** Same as **b)** but displaying vertical bars that represent local summer and local winter mean (i.e. the warmest 100 warmest months and coldest 100 coldest months). The squares (red) and circles (black) represent marine and terrestrial proxy-based temperature anomalies, respectively. The solid thick lines represent the 1 : 1 line that indicates a perfect match of ~~modelled~~simulated and reconstructed anomalies.

Figure ~~11~~9. Timing of the maximum Last Interglacial warmth (in kyr BP) for: **(a)** local summer (warmest 100 warmest months) and **(b)** annual mean (warmest 100 model years) derived from the LIG-1300~~-~~m-alb-tr simulation, between 130 and 120 kyr BP. ~~The squares and circles in **(a)** indicate the location of the marine and terrestrial proxies by CAPE Last Interglacial Project Members (2006). The circles in **(b)** indicate the location of the terrestrial proxies by Turney and Jones (2010).~~

Figure 10. Effect of **(a, b)** Greenland Ice Sheet elevation, insolation, albedo, and atmospheric methane concentration and **(c, d)** insolation and atmospheric methane concentration at 130 kyr BP relative to

preindustrial (PI). Model-data comparison of mean local summer temperature anomalies (in °C). The shading represents the simulated surface temperature (TS) anomalies derived from **(a, b)** LIG- 1300 m-alb simulation and **(c, d)** LIG-ctl simulation. Hatched areas mark statistically insignificant TS anomalies. The squares show marine proxy-based LIG summer temperature anomalies relative to present-day derived by Capron et al (2014).

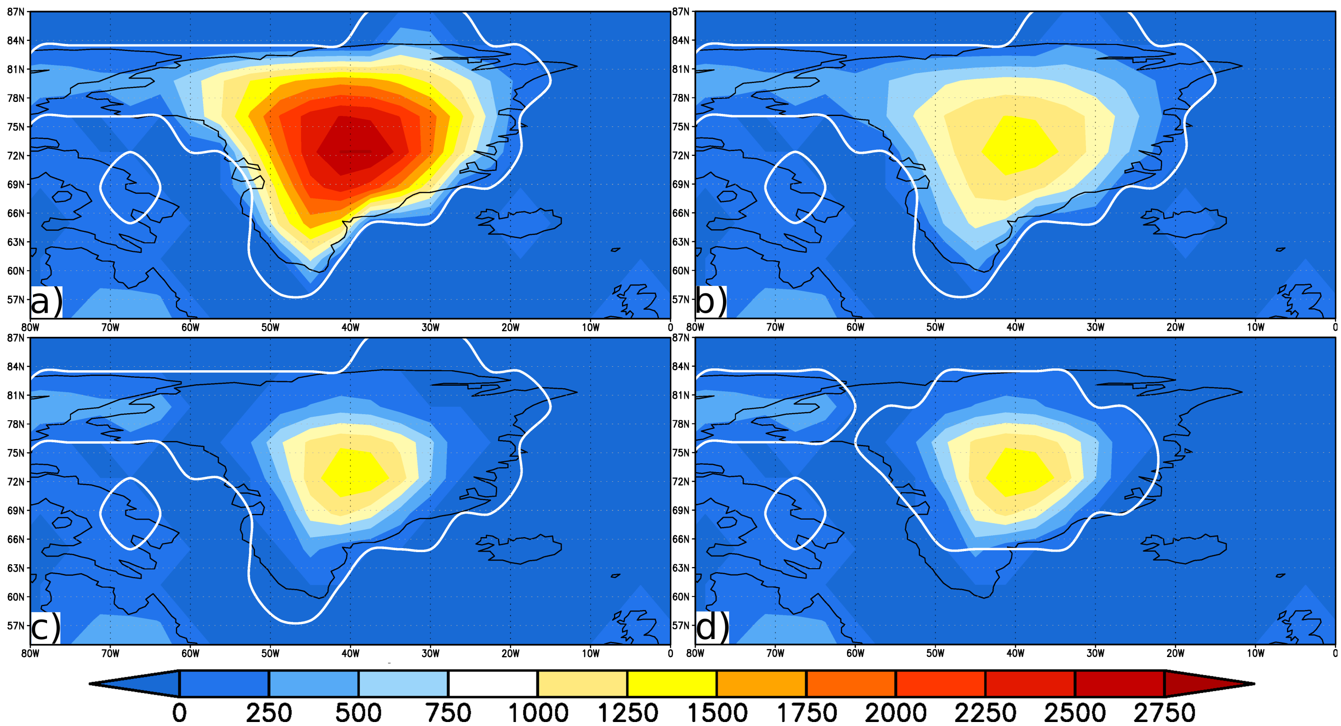
Figure 11. Effect of **(a–c)** Greenland Ice Sheet elevation and **(c)** albedo on sea level pressure (SLP) and surface winds in 130 kyr BP simulations. The shading represents December-January-February (DJF) mean SLP anomalies (in Pa), superimposed by DJF mean surface wind anomalies (in ms^{-1}) for: **(a)** LIG-×0.5 minus LIG-ctl, **(b)** LIG-1300m minus LIG-ctl, and **(c)** LIG-1300m-alb minus LIG-ctl simulations. The vector length indicates the wind speed (in ms^{-1}).

Simulation	Time (kyr BP)	CO_2 (ppmv)	CH_4 (ppbv)	N_2O (ppbv)	Greenland Ice Sheet	Veg.	e	ε (°)	ω (°)
LIG-ctl	130	278	650	270	PI	dyn.	0.0382	24.24	49.1
LIG-×0.5	130	278	650	270	×0.5	dyn.	0.0382	24.24	49.1
LIG-1300m	130	278	650	270	-1300m	dyn.	0.0382	24.24	49.1
LIG-1300m-alb	130	278	650	270	-1300m+alb	dyn.	0.0382	24.24	49.1
LIG-1300m-alb-CH_4	130	280	760	270	-1300m+alb	dyn.	0.0382	24.24	49.1
LIG-GHG*	130	257	512	239	PI	PI	0.0382	24.24	49.1
LIG-125k*	125	278	650	270	-1300m+alb	dyn.	0.0400	23.79	128.1
~~GI*~~	~~115~~	~~278~~	~~650~~	~~270~~	~~-1300m+alb~~	~~dyn.~~	~~0.0414~~	~~22.40~~	~~291.8~~
~~HOL-×0.5*~~	~~6~~	~~278~~	~~650~~	~~270~~	~~×0.5~~	~~dyn.~~	~~0.0187~~	~~24.10~~	~~181.8~~
PI	0	280	760	270	PI	dyn.	0.0167	23.45	282.2
LIG-ctl-tr	130-115	278	650	270	PI	dyn.	varying	varying	varying
LIG-×0.5-tr	130-115	278	650	270	×0.5	dyn.	varying	varying	varying
LIG-1300m-alb-tr	130-115	278	650	270	-1300m+alb	dyn.	varying	varying	varying
LIG-GHG-tr	130-115	varying	varying	varying	PI	PI	varying	varying	varying
HOL-tr	8-0	278	650	270	PI	dyn	varying	varying	varying

Table 1

		Annual mean ~~SAT~~TS (°C)			Winter mean ~~SAT~~TS (°C)			Summer mean ~~SAT~~TS (°C)		
Simulation	AMOC (Sv)	global	NH	SH	global	NH	SH	global	NH	SH
LIG-ctl	12.8	14.77	15.57	13.98	8.76	6.53	10.98	21.00	24.78	17.22
LIG-×0.5	13.3	15.13	16.03	14.22	9.19	7.12	11.25	21.25	25.09	17.41
LIG-1300m	14.8	15.07	15.95	14.18	9.14	7.05	11.22	21.17	24.96	17.39
LIG-1300m-alb	15.0	15.14	16.00	14.29	9.24	7.10	11.37	21.24	25.02	17.46
LIG-1300m-alb-CH_4	14.4	15.32	16.34	14.29	9.40	7.49	11.31	21.43	25.35	17.50
LIG-GHG	12.8	14.65	15.50	13.80	8.69	6.56	10.82	20.82	24.64	17.00
LIG-125k	14.8	15.19	16.11	14.27	9.46	7.74	11.17	21.20	24.94	17.46
~~GI~~	~~19.9~~	~~14.77~~	~~15.60~~	~~13.94~~	~~9.36~~	~~8.27~~	~~10.45~~	~~19.94~~	~~22.13~~	~~17.76~~
~~HOL-×0.5~~	~~14.3~~	~~15.01~~	~~15.84~~	~~14.18~~	~~9.36~~	~~7.89~~	~~10.84~~	~~20.74~~	~~23.79~~	~~17.70~~
PI	16.3	14.51	15.35	13.67	8.84	7.44	10.23	20.09	22.84	17.33

Table 2



a)
b)
c)
d)
87N
84N
81N
78N
75N
72N
69N
66N
63N
60N
57N
80W
70W
60W
50W
40W
30W
20W
10W
0
0
250
500
750
1000
1250
1500
1750
2000
2250
2500
2750

Figure 1

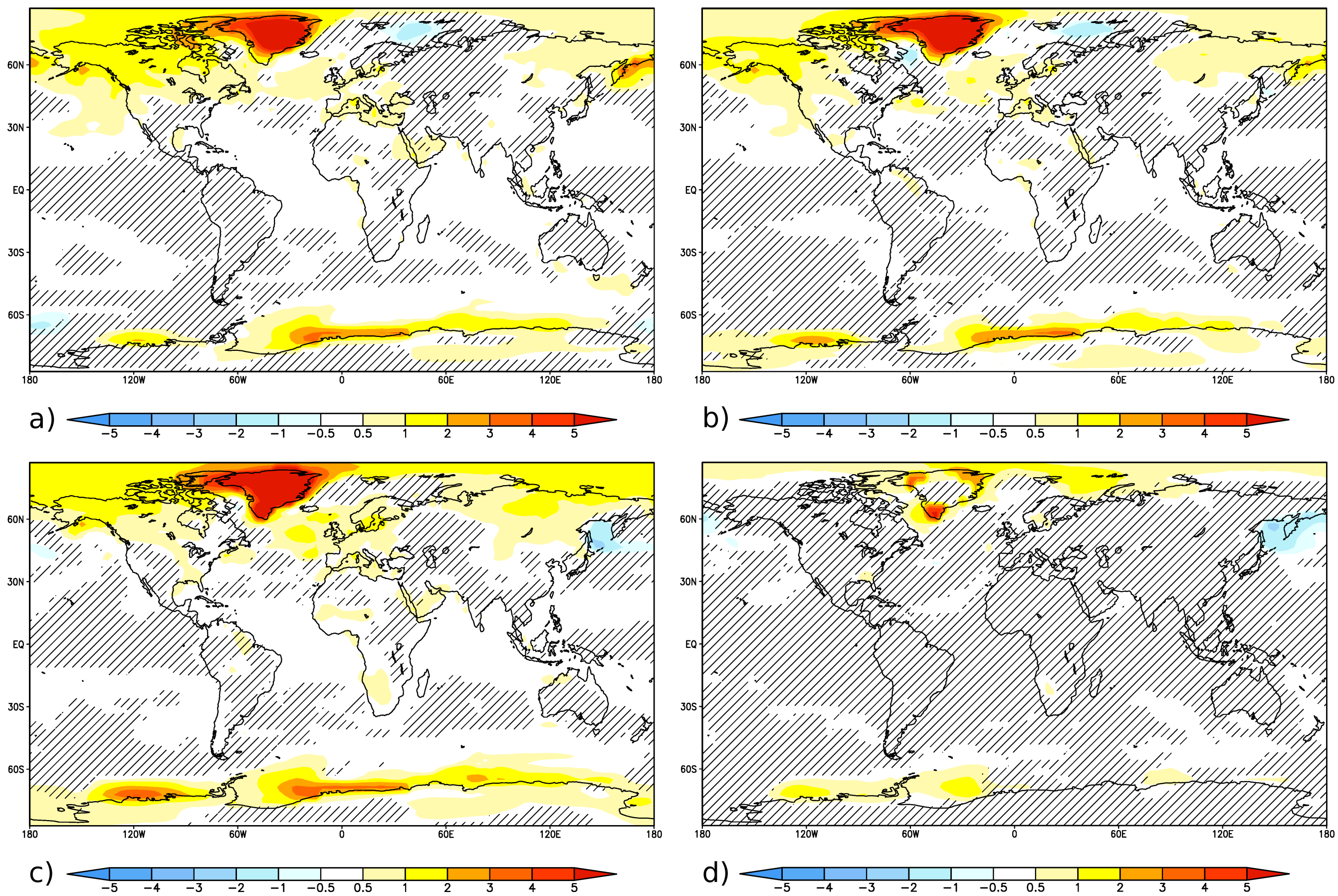

60N
30N
EQ
30S
60S
180
120W
60W
0
60E
120E
180
a)
b)
c)
d)
−5
−4
−3
−2
−1
−0.5
0.5
1
2
3
4
5

Figure 2

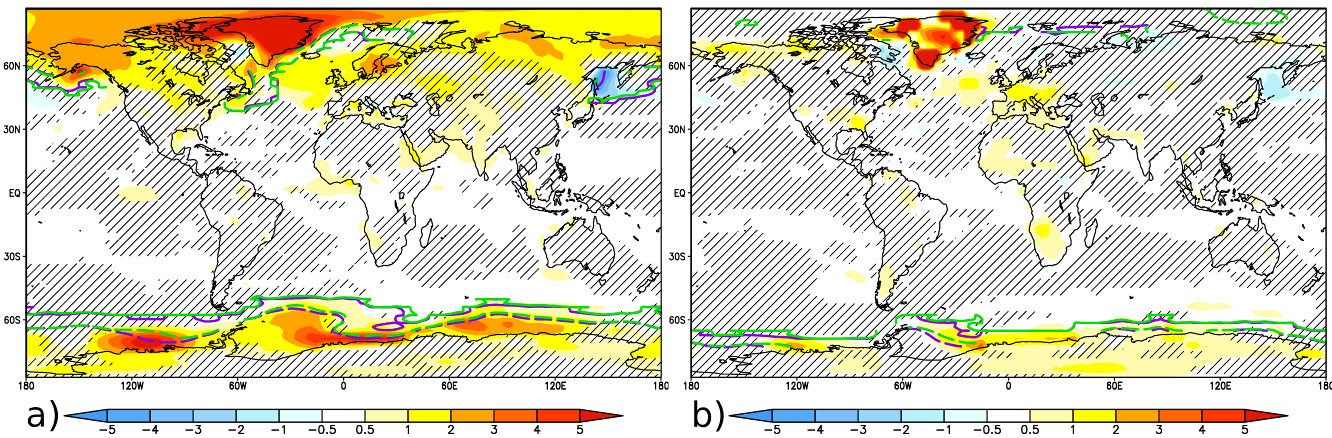

60N
30N
EQ
30S
60S
180
120W
60W
0
60E
120E
180
a)
−5
−4
−3
−2
−1
−0.5
0.5
1
2
3
4
5
b)

Figure 3

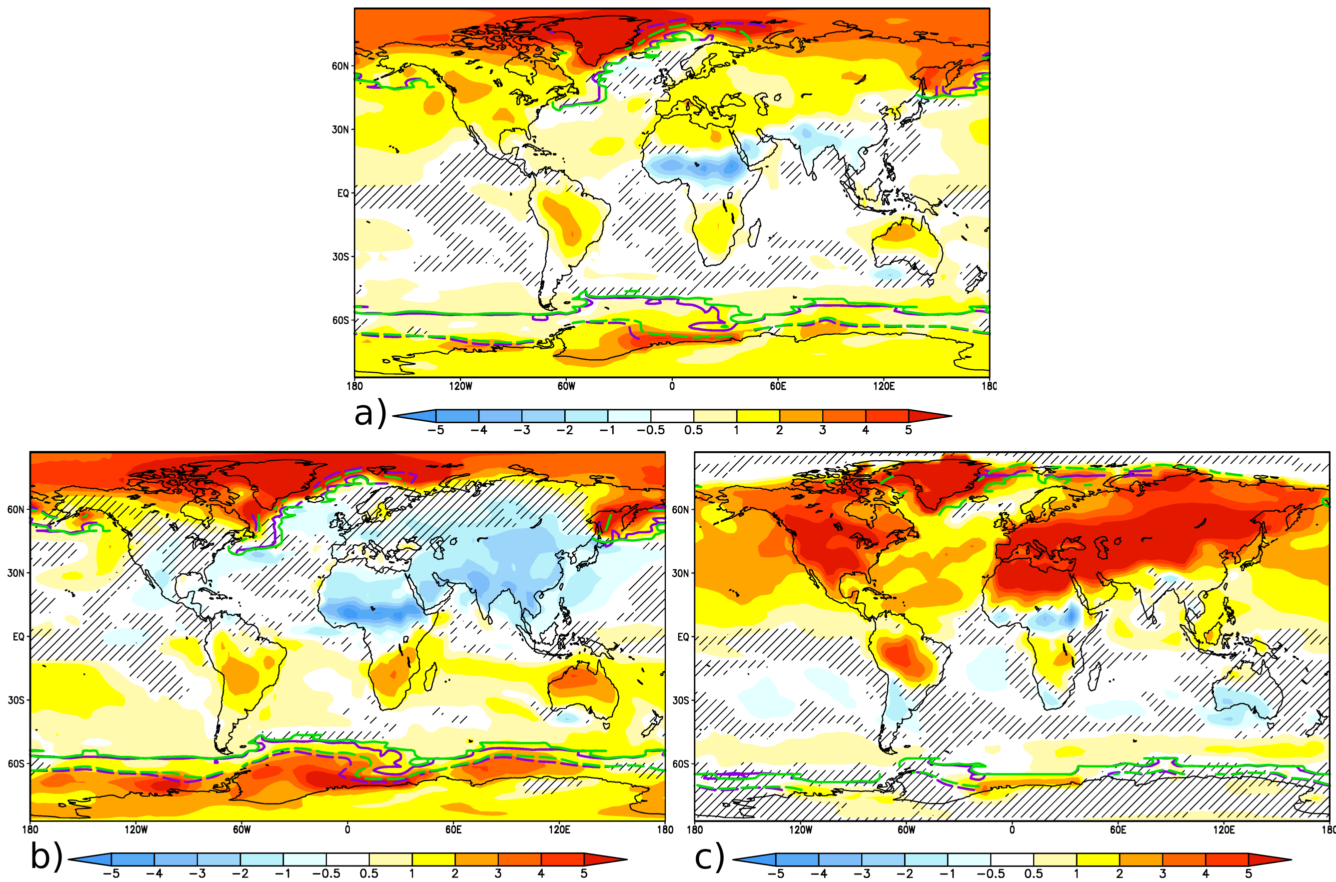

60N
30N
EQ
30S
60S
180
120W
60W
0
60E
120E
180
a)
−5 −4 −3 −2 −1 −0.5 0.5 1 2 3 4 5
b)
−5 −4 −3 −2 −1 −0.5 0.5 1 2 3 4 5
c)
−5 −4 −3 −2 −1 −0.5 0.5 1 2 3 4 5

Figure 4

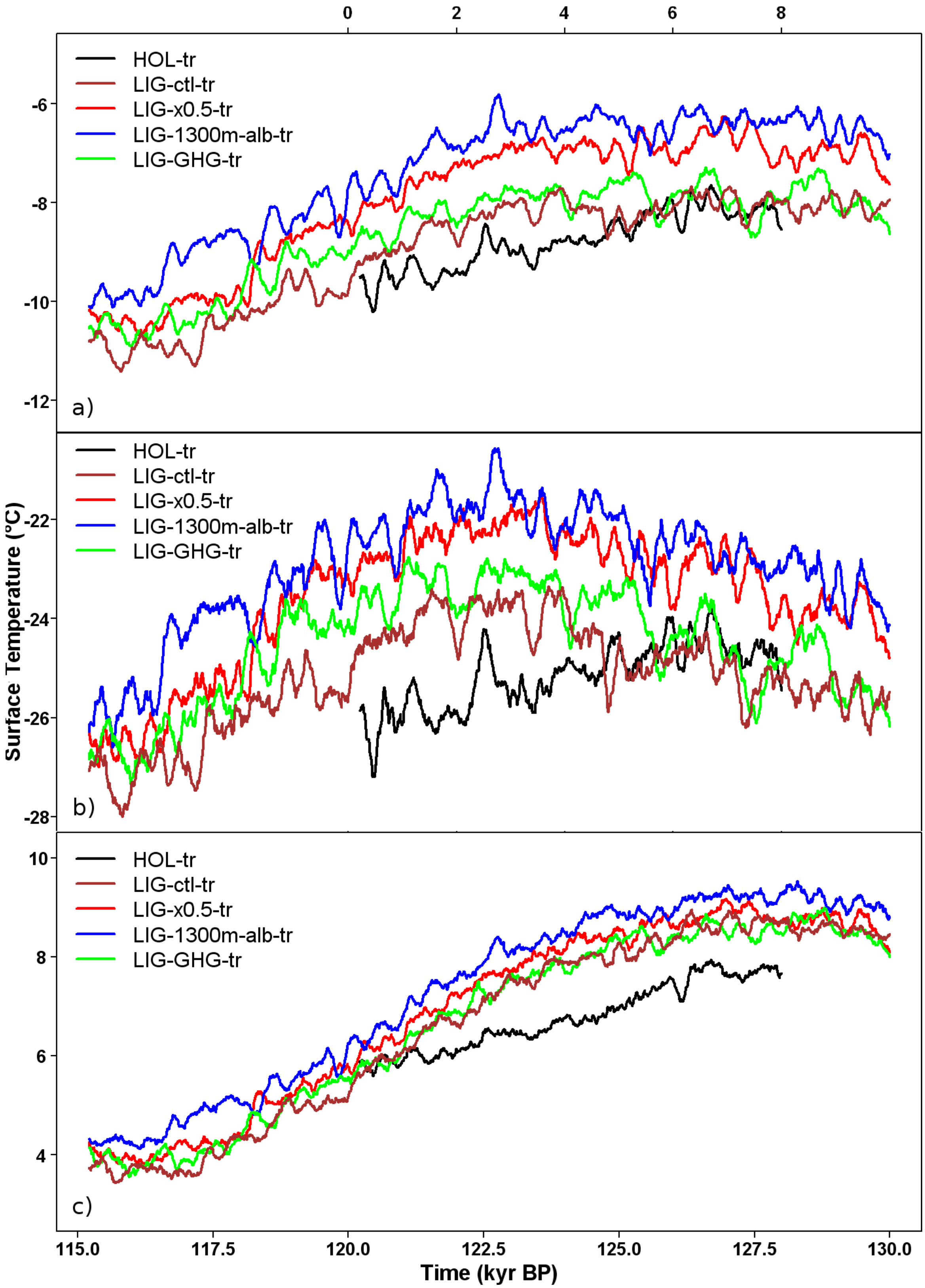

0
2
4
6
8
HOL-tr
LIG-ctl-tr
LIG-x0.5-tr
LIG-1300m-alb-tr
LIG-GHG-tr
-6
-8
-10
-12
a)
HOL-tr
LIG-ctl-tr
LIG-x0.5-tr
LIG-1300m-alb-tr
LIG-GHG-tr
-22
-24
-26
-28
b)
Surface Temperature (°C)
HOL-tr
LIG-ctl-tr
LIG-x0.5-tr
LIG-1300m-alb-tr
LIG-GHG-tr
10
8
6
4
c)
115.0
117.5
120.0
122.5
125.0
127.5
130.0
Time (kyr BP)

Figure 5

~~**Figure 7**~~

~~**Figure 6**~~

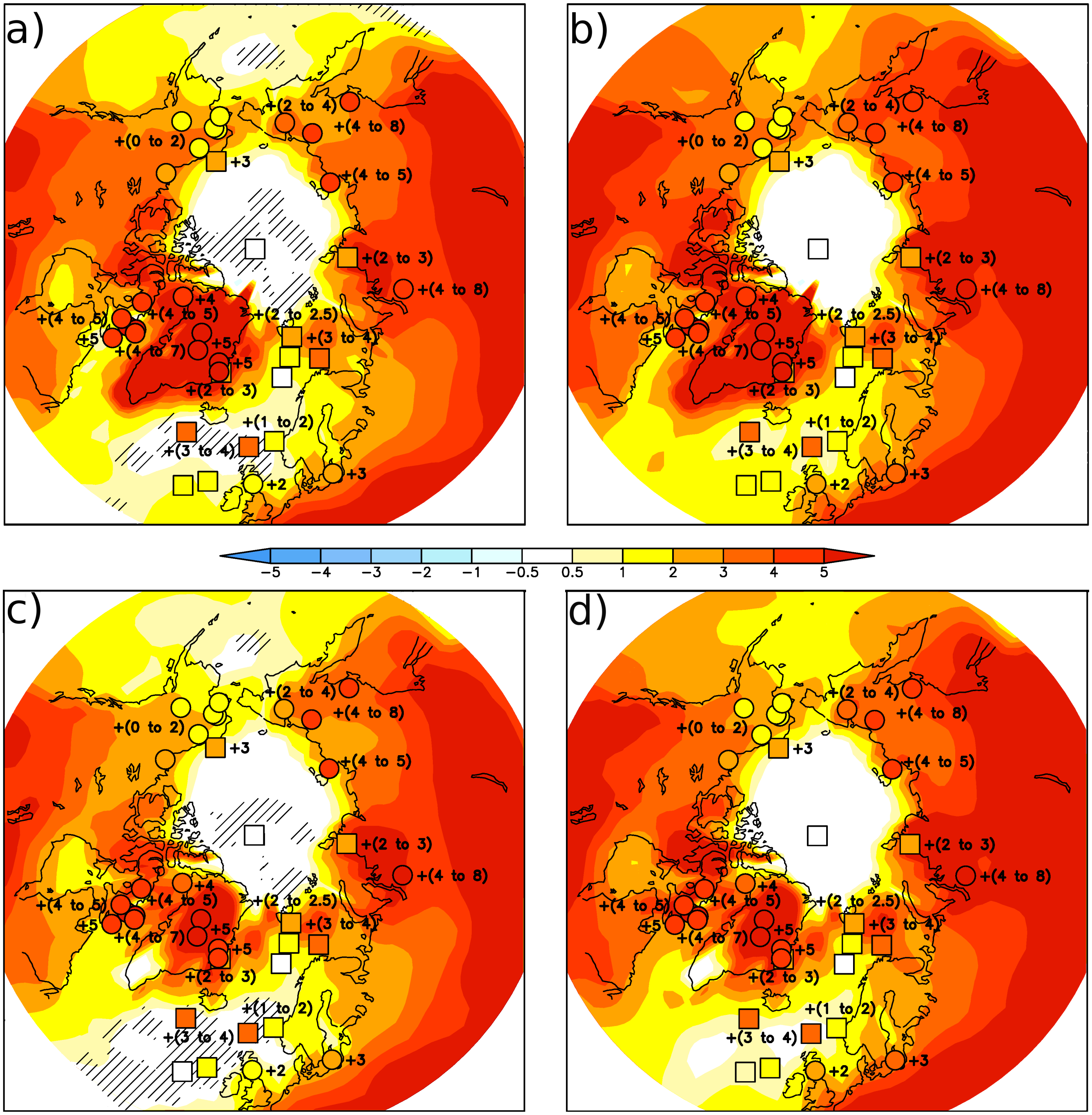
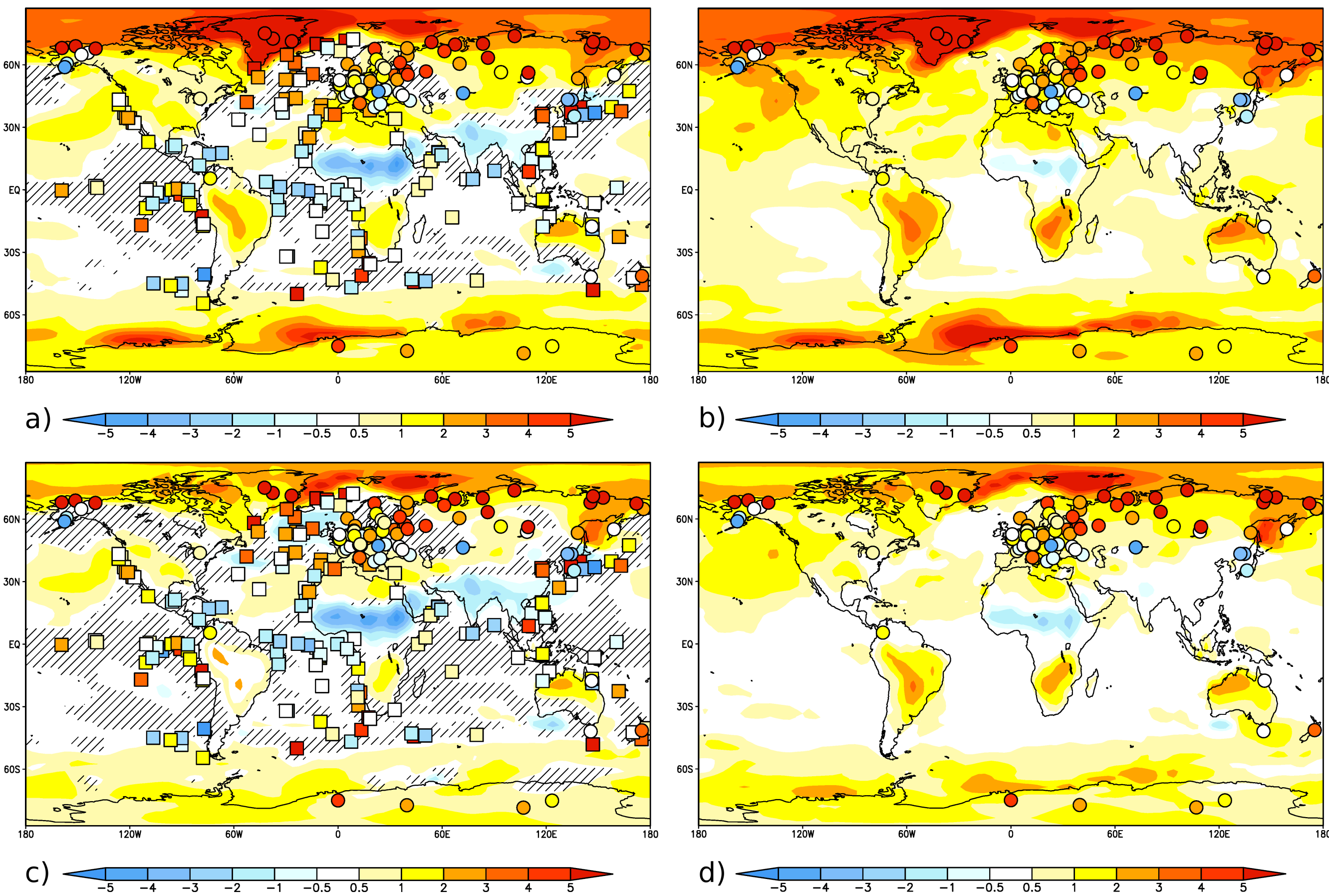

a)
b)
c)
d)
+(0 to 2)
+3
+(2 to 4)
+(4 to 8)
+(4 to 5)
+(2 to 3)
+(4 to 8)
+4
+(4 to 5)
+(2 to 2.5)
+(4 to 5)
+5
+(4 to 7)
+5
+(3 to 4)
+5
+(2 to 3)
+(1 to 2)
+(3 to 4)
+2
+3
−5
−4
−3
−2
−1
−0.5
0.5
1
2
3
4
5

Figure 68



a)
b)
c)
d)
60N
30N
EQ
30S
60S
180
120W
60W
0
60E
120E
180
−5 −4 −3 −2 −1 −0.5 0.5 1 2 3 4 5

Figure 97

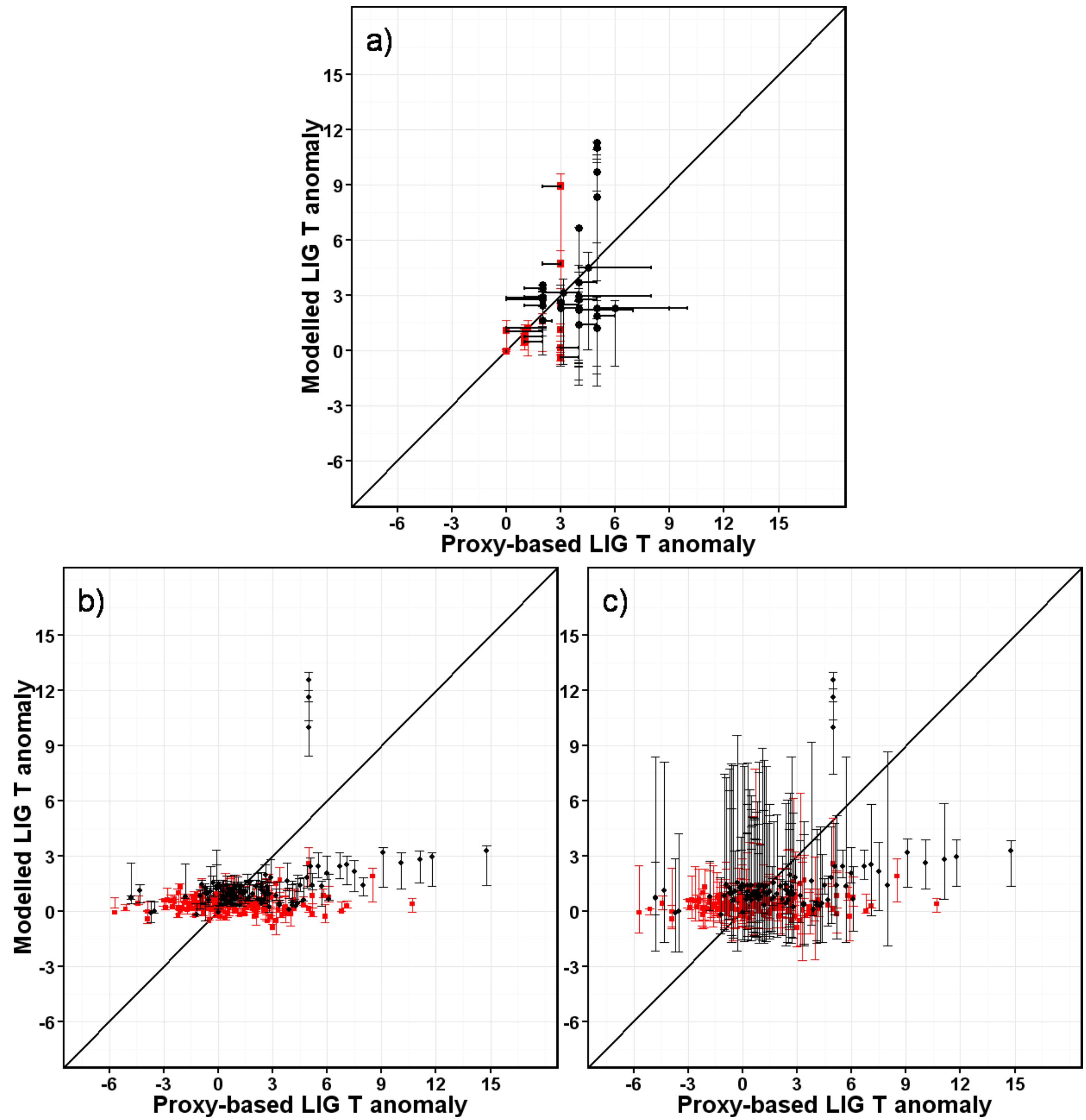
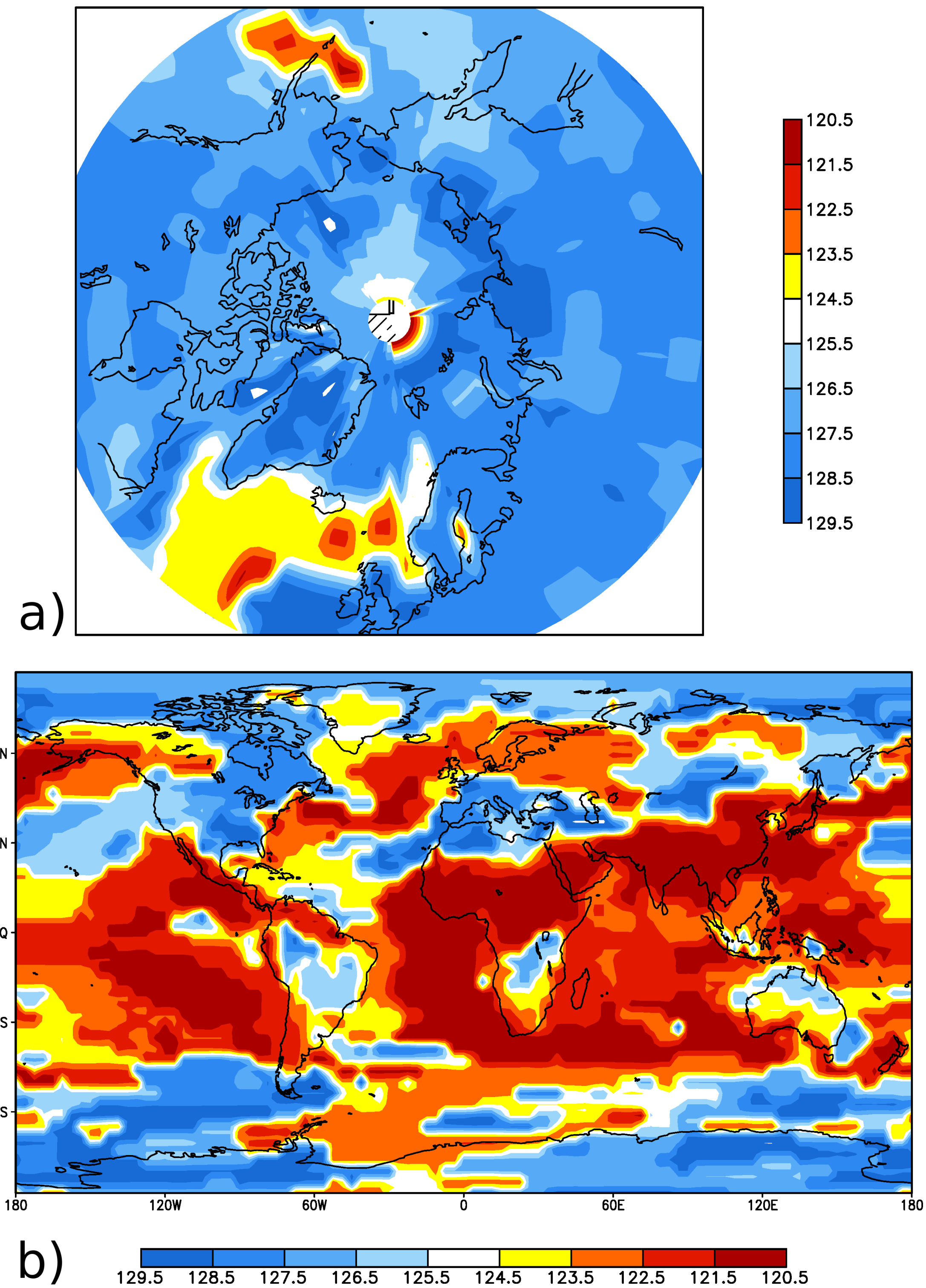

a)
b)
c)
Modelled LIG T anomaly
Proxy-based LIG T anomaly
-6
-3
0
3
6
9
12
15

Figure ~~10~~8



120.5
121.5
122.5
123.5
124.5
125.5
126.5
127.5
128.5
129.5
a)
60N
30N
EQ
30S
60S
180
120W
60W
0
60E
120E
180
b)
129.5
128.5
127.5
126.5
125.5
124.5
123.5
122.5
121.5
120.5

Figure ~~11~~9

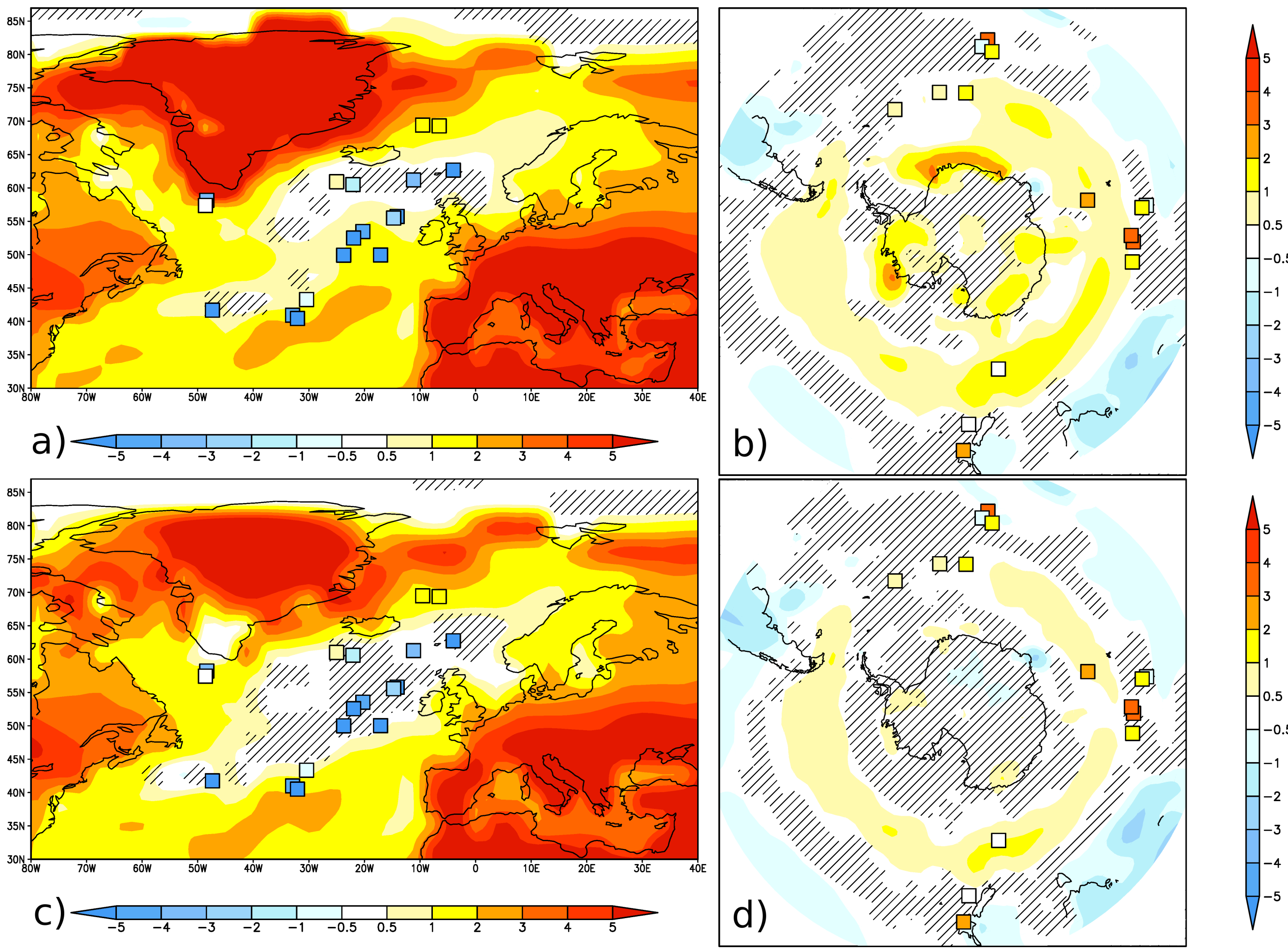

85N
80N
75N
70N
65N
60N
55N
50N
45N
40N
35N
30N
80W
70W
60W
50W
40W
30W
20W
10W
0
10E
20E
30E
40E
a)
b)
c)
d)
−5 −4 −3 −2 −1 −0.5 0.5 1 2 3 4 5

Figure 10

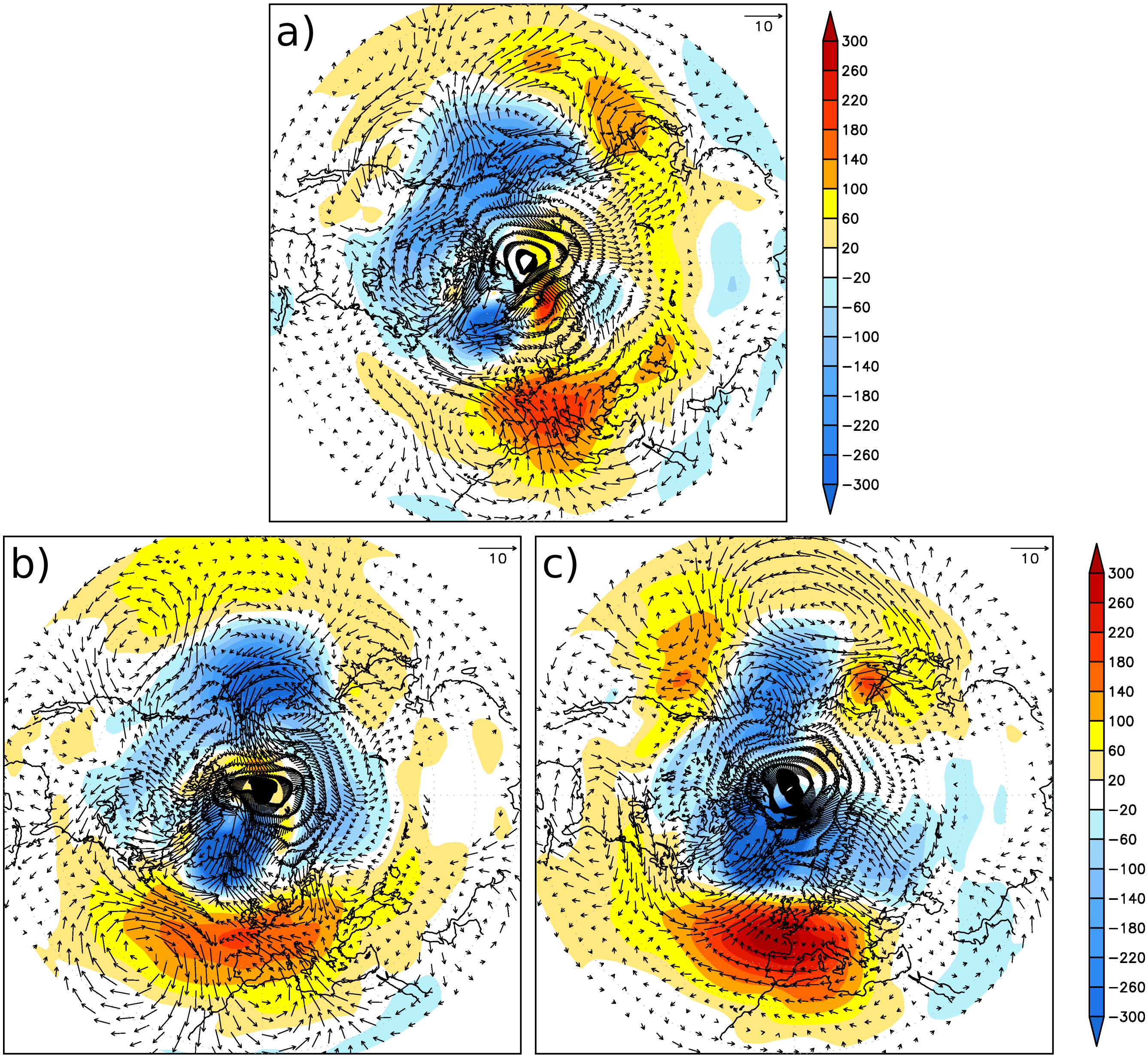

a)
b)
c)
10
10
10
300
260
220
180
140
100
60
20
−20
−60
−100
−140
−180
−220
−260
−300

Figure 11