Reply to comments of Referee #2

We thank referee #2 for an extensive and constructive review. Editorial and technical recommendations will be followed while rewriting the CPD manuscript, and all concerns/questions as discussed below will be addressed.

Specific comments:

Referee #2: *1) The authors conclude that "the simulated summer temperatures follow the general pattern of the sediment core data" (p.4457, l.5). This conclusion is based on visual inspection alone (Fig. 4) and difficult to follow. It is unclear how the authors define "general pattern". The SST record of core MD95-2010 shows a warming of about 3 K from 130 ka to 125 ka and a subsequent cooling of the same magnitude until 115 ka. The model shows a warming of only 1 K from 130 ka to 125 ka, resulting in a temperature bias of about 3 K around at 125 ka. The model-data disagreement is even worse for core ODP 980 at 130 ka, where the model has a cold bias of almost 4 K at 125 ka. For core EW9302-JPC2 the model fails at simulating the dramatic temperature increase around 125 ka. The model-data comparison should be more quantitative. a) Which trends are simulated, which are not? b) Does the model capture the reconstructed temperature variance? c) For which time slice is the model-data mismatch best/worst? d) Statistical parameters should be used but this would probably require the use of more proxy records as e.g. in Lunt et al. (2013, Clim. Past) (Why do the authors restrict their model-data comparison to these four records in the North Atlantic?) A recent example for an insightful model-data comparison can be found in Milker et al. (2013, Clim. Past), albeit for another interglacial period. e) Proxy-related uncertainties can explain only a part of the model-data mismatch, but it would be helpful to include error bars/envelopes for the proxy records into Fig. 4 considering both uncertainties in the paleothermometry as well as in the age model.*

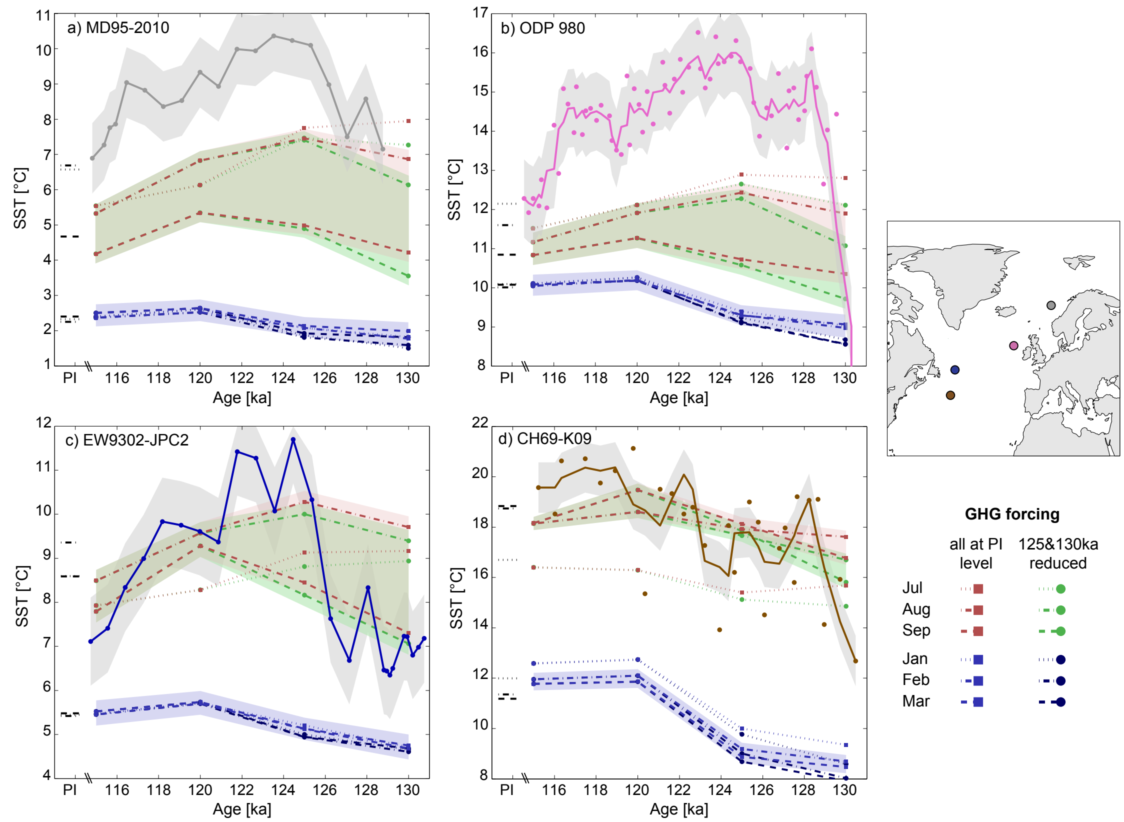
a) The reconstructed temperature trends are described in the first part of Section 3.2. b) Shorter term variations on top of this cannot be replicated with time slice simulations, and therefore we only focus on the long term trends (>~5k).

c) For 130 ka the model-data match is worst, as the reconstructed cold SSTs at that time are not simulated. However by reducing GHG concentrations the simulated 130 ka SSTs are decreased, thereby reducing the mismatch between the model and the reconstructions.

d) The focus of this study is the temporal evolution during the LIG, which can only be assessed using high-resolution records that are constrained to one common time scale. A global dataset combining LIG SSTs on a common time scale is not available, yet. That is why we focus on these four records and not on the time mean dataset of Turney and Jones (2010) used by Lunt et al. (2013).

e) In order to better show the SST trends and associated uncertainties, we

indicate an uncertainty in the SST reconstructions and also shade the likely modeled SST trend in the updated figure 4 (see below).
In addition to the updated figure, the discussion of the model-data comparison in the revised manuscript will be expanded as well as the discussion of the differences to the study of Lunt et al. (2013). See also reply to reviewer #1.

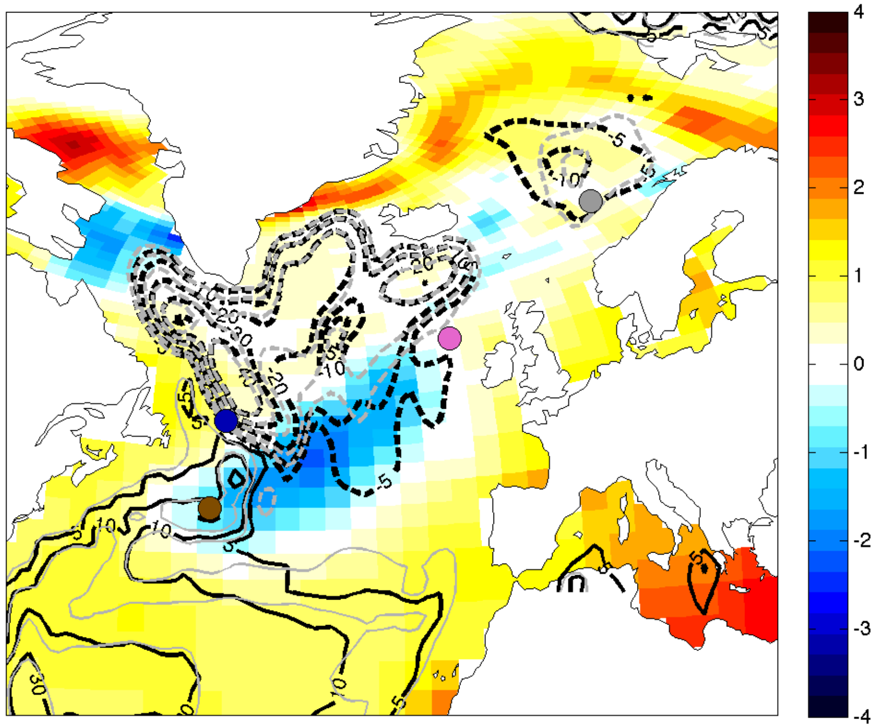


Updated Fig. 4: Reconstructed (solid lines) and modeled (dashed and dotted lines) sea-surface temperatures (SST) for the four core locations. (a) Norwegian Sea core MD95-2010; (b) North Atlantic core ODP 980; (c) Labrador Sea core EW9302-JPC2; and (d) North Atlantic core CH69-K09. The red-brown and blue lines indicate the modeled last interglacial SST evolution with greenhouse gas forcing kept constant at pre-industrial levels for Jul-Aug-Sep and Jan-Feb-Mar, respectively. The green and dark blue lines show the simulated temperatures due to reduced greenhouse gas forcing at 125 ka and 130 ka. The colored shading indicates the best fitting summer (Aug and Sep; red for constant GHG forcing and green for reduced GHG forcing) and winter (Feb and Mar; blue, only shown for constant GHG forcing) months. The grey shading around the proxy data indicates possible errors and is set to 1°C. The horizontal bars on the left side of the figures indicate modeled PI monthly mean values.

Referee #2: *2) What are the reasons for the modelled temperature trends? Direct insolation forcing can explain only a part of the variance. In particular, core CH69-K09 shows a positive temperature trend through the LIG which seems to be partly captured by the model. The authors briefly mention changes in the subpolar gyre extent as a possible cause for the observed temperature trend in the mid-latitude North Atlantic. Some figures illustrating these circulation changes* *should be included. What is the reason for the changes in the gyre circulation? How do the westerly winds behave?*

The main trend of increasing temperatures from 130 to 125 ka, and the decreasing temperatures from 125 ka to 115 ka, is the result of summer insolation changes over the North Atlantic (see Fig 1d). The mid-Atlantic cooling simulated at 125 and 130 ka is most likely due to a southeast-expansion of the subpolar gyre as discussed in reply to reviewer #1.

In the revised manuscript we will include a new figure showing the simulated changes to the subpolar gyre as given by the horizontal streamfunction plotted together with the corresponding SST anomalies (see also below). The section describing figure 5 (last paragraph of Section 3.2) will be expanded with a discussion of the cooling and its relationship to changes to the subpolar gyre, and will include the new figure.



New figure #1: Horizontal streamfunction [Sv] showing the subpolar gyre on top of 130 ka_Gpi-PI SST anomalies [ºC]. Bold contour lines indicate 130 ka_Gpi and thin lines PI. Core site locations are shown as colored dots.

Referee #2: *3) a) It would also be helpful to include more information on the model cold bias observed for the two northermost cores MD95-2010 and ODP 980. Does the model also produce a cold bias for the modern climate (maybe due to shortcomings in the simulation of oceanic or atmospheric heat transports)? Again, more in-depth analysis of physical mechanisms is needed. b)*

The same holds for the explanation of the Southern Ocean early LIG temperature maximum which obviously does not follow the local insolation during summer (DJF). The short paragraph on p.4459, l.23-28 is insufficient. The statement "summer insolation is efficiently stored and results in warm surface temperatures also in winter" is meaningless. It rather appears that, to first order, local winter (JJA) insolation controls the Southern Ocean temperatures year-round. Or maybe another season (SON, MAM) may play a crucial role in driving the year-round temperature trend. An in-depth analysis of this interesting phenomenon should be carried out.

a) Yes, the NorESM model has a cold bias at high northern latitudes in the pre-industrial climate, due to relatively weak inflow of warm Atlantic water. This will be noted in the revised manuscript.

b) Indeed, the high SON insolation during early LIG causes the Southern Ocean to warm. See reply to reviewer #1 on this issue, which will be carefully addressed in the revised manuscript.

Minor points:

Referee #2: *1) p.4441, l.5: The 7 m higher sea level inferred by Kopp et al. (2009) was not during the early LIG, but rather after ca. 125 ka BP.*

OK, we will reword this sentence.

Referee #2: *2) I suppose experiments 125 ka and 130 ka are identical to those published in Lunt et al. (2013, Clim. Past). If this is correct, please state so.*

Yes, we will mention this.

Referee #2: *3) How are ozone and aerosol distributions treated?*

They are kept the same as in the pre-industrial simulation. We will mention this.

Referee #2: *4) Is a fixed modern calendar used for the definition of months and seasons? If so, this may cause some problems as shown by e.g. Chen et al. (2011, Clim. Dyn.). Unless the authors use a fixed-angular calendar they should discuss why the use of a fixed-day calendar does not affect their results and conclusions.*

We use a fixed-day calendar (with spring equinox fixed to March 21st) as is commonly used for LIG simulations (e.g. all simulations in Bakker et al., 2013; Lunt et al., 2013). This could cause a bias when looking at a particular month. The effect of not using a fixed-angular calendar is largest for the late autumn (SON) months. For spring (MAM) the difference is close to zero (see also Chen et al., 2011).

In figure 4 we compare simulated monthly-mean ocean temperatures to reconstructed SSTs. Because of the fixed-day calendar we compute months based on fixed days of the year. For example, today July contains days 181 to

210. However, due to the change in precession, at 126 ka July shifts by a number of days to 176 to 202 (Chen et al., 2011). Our fixed-calendar “July” therefore contains some (~5) days of August in the early LIG simulation. Vice versa it contains some days on June in the late LIG. The correct fixed-angular evolution of the LIG summer months would therefore be slightly different than the curves shown in figure 4. However, as we include several summer months in the analysis, and the main conclusion is that the proxy records show a summer signal (in the broad sense), the use of a fixed-day calendar in the model will not significantly bias the main conclusions based on this figure.
The same is true for figure 5, which shows maps of August temperatures; the shift in the calendar will not alter the simulated sea surface temperature patterns.
Unfortunately we did not save the daily model output due to the exceedingly large amount of data storage required, so we cannot recalculate the monthly mean values presented in the manuscript. However, we very much appreciate the reviewers comment and will recalculate the monthly mean values in future simulations. As a simple test of the impact on the results, we shifted the definition of the months through time by including 20% of the month before or after in calculating the JJA and DJF means given in figure 6, and the main pattern of early JJA warming and late DJF warming is still valid. Therefore we do not think that the definition of the calendar will change our main results.
The issue of using models with a fixed-day calendar for paleoclimate studies will be addressed in the revised version of the manuscript.

Referee #2: *5) p.4455, l.21: "In the SH the early last interglacial summer/autumn insolation is enhanced, while winter insolation is reduced". I think it’s the other way round.*
This will be corrected in the revised manuscript.

Referee #2: *6) p.4456, l.12: Northern hemisphere polar amplification during DJF is clearly visible in Fig. 3 in response to GHG forcing. Please discuss. Moreover, how do the results compare to previous LIG simulations by e.g. Yin and Berger (2012, Clim. Dyn.) in terms of the individual roles of GHG and orbital forcing?*
Yin and Berger (2012) also conclude that GHG control the annual mean temperatures, and that insolation plays a dominant role over the northern high latitudes. However they also find that southern high latitudes are mostly controlled by GHG forcing, while we find also an insolation effect. However it is difficult to compare our results directly as they take the insolation and GHG values from 127 ka, where GHG were slightly higher than at PI, in contrast to our reduced GHG values at 130 and 125 ka.
Polar amplification and the comparison to Yin and Berger (2012) will be included in Section 3.1 of the revised manuscript.

Referee #2: *7) p.4460, l.25: The authors only discuss the possible influence of meltwater on early LIG high-latitude cooling. However, northern hemisphere ice* *sheets probably contributed to a global sea level drop of about 20 m around 130 ka BP (Kopp et al., 2009, Nature), i.e. the remnants of big glacial ice sheets might have substantially affected high-latitude climate through albedo and topography in a similar way as in the early Holocene (see Renssen et al, 2009, Nature Geo.). Please discuss.*

As the focus of this study was to isolate the effects of GHG and insolation forcing during the LIG and not on the deglaciation of large land based ice masses, we did not include ice sheet meltwater, topography and albedo changes in our model simulations.

Renssen et al. (2009) show that meltwater, albedo and topography changes can decrease the North Atlantic SST values by 1-3 degrees during the early Holocene. Note however, that the combined effect of these different factors are not well resolved: as shown in a sensitivity study with an atmospheric GCM by Pausata et al. (2011), who used an atmospheric GCM, the albedo and topography of the LGM Laurentide ice sheet have opposite effects on Atlantic SSTs.

The possible additional cooling effect due to remnants of the Northern Hemisphere ice sheets early in the LIG will be discussed in relationship to the proxy data in Section 3.2 of the revised manuscript.

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