Reply to comments of Referee #1

We thank referee #1 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.

Main concerns

Referee #1: *Section 3.1 Since a number of studies (like Lunt et al., 2013) have presented LIG snapshot simulations previously I think a more thorough comparison and discussion should be included.*

A more extensive description of the Lunt et al. (2013) study will be included in the introduction. The NorESM experiments following the PMIP protocol for 130 ka and 125 ka are part of the early LIG model intercomparison. As shown in Lunt et al. (2013), several of the participating models simulate relatively cold winter and warm summer seasons early in the LIG (125-130 ka) as well as a smaller annual mean temperature response in accordance with our study.

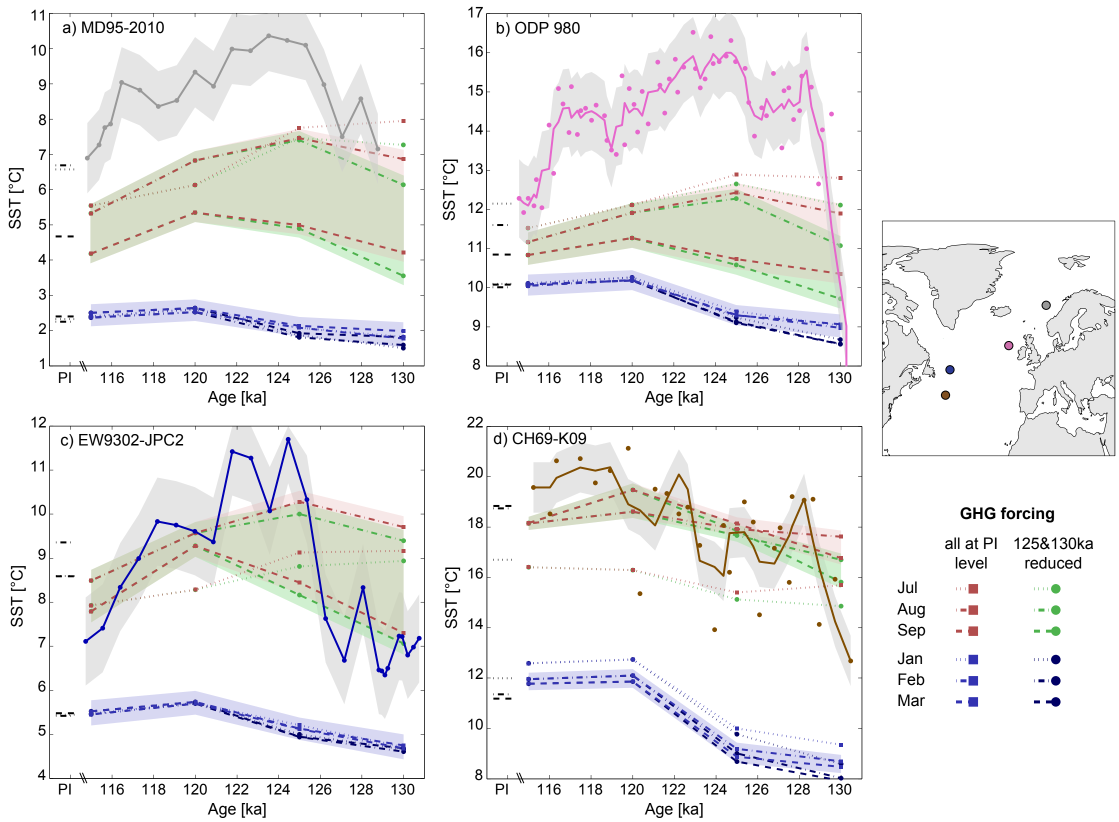
A comparison and discussion will be included in the introduction of the revised manuscript.

Referee #1: *Section 3.2 A comparison is made in figure 4 between reconstructed SSTs at different North Atlantic sites and simulated monthly temperatures. The fact that monthly values are used rather than summer mean values like JJA makes that this manuscript goes more into depth than previous studies. However, in section 3.2 only JAS values are discussed. Please describe the important differences between the different months; specify and discuss which ones fit to the reconstructions and which don't.*

August and September are the months that fit best, depending on the location. For the northern most sites (MD95-2010 and ODP 980) the maximum SST is reached at 125 ka. August is the only modeled month that has its maximum at 125 ka. Therefore, combined with a similar decrease after the peak warmth, this month fits the reconstructed SST pattern best. For EW9302-JPC2 the temperature peak is also reached at 125 ka (which fits again modeled August SSTs). However it also shows a rapid SST increase before this optimum, and this fits the modeled September better. In the southernmost core (CH69-K09) an increase in SST is registered, with a flattening and possible decrease between 118-114 ka. The modeled month that captures this increase best is September.

However, it should be noted that the proxy records represent not just one month. Therefore, in order to compare our modeled results to the proxy derived SSTs we use shading to indicate the general summer and winter trends as computed by the model. Also a 1°C error on the data has been included in the shading (see updated figure 4 below).

We will include this discussion and the updated figure 4 in Section 3.2 of the revised manuscript.



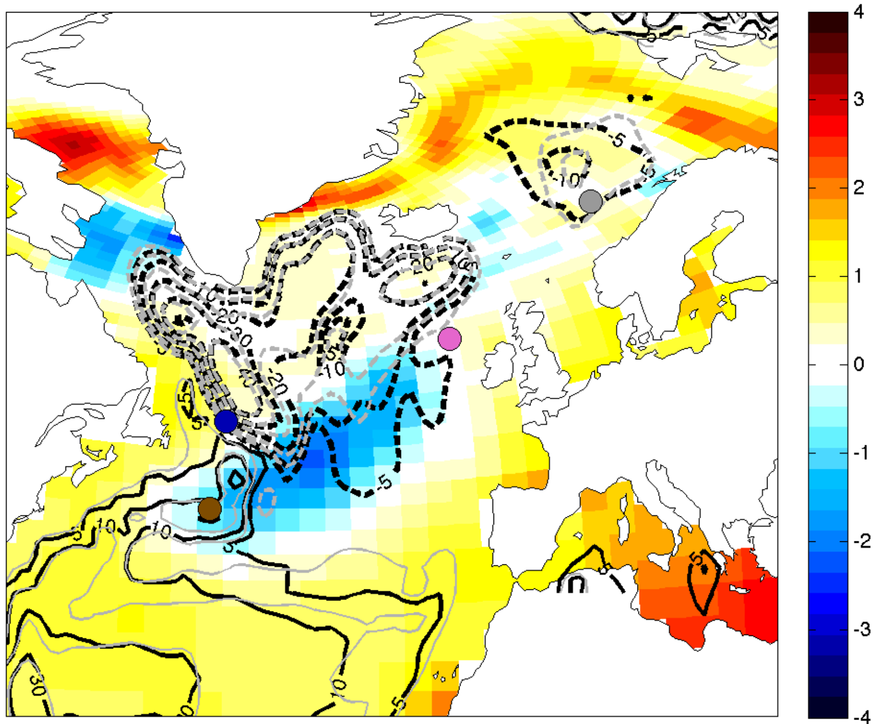
Updated Fig. 4: Reconstructed (solid lines) and modeled (dashed and dotted lines) sea-surface temperatures (SST) for the four core locations. (a) Norwegian Sea core MD95-2010; (b) North Atlantic core ODP 980; (c) Labrador Sea core EW9302-JPC2; and (d) North Atlantic core CH69-K09. The red-brown and blue 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 #1: *4457.17 According to Figure 4 the impact of including early LIG GHG values in the simulations is rather limited (1 degree at most). Is that sufficient to explain the lower early LIG temperatures as described for instance by Govin et al. (2012)? Furthermore, the word 'significant' will make the reader wonder how you calculated this significance, at what confidence level etc.*

The word 'significant' is deleted, as it is not possible to compute a confidence level on this few data points. Govin et al. (2012) find a ~1°C annual mean cooling at the locations of the 3 southern core sites in a model simulation perturbed with a large northern meltwater input (their Fig. 10a). For the summer season the temperature response is the same order of magnitude (pers. comm.). So both effects (reduced GHG values and freshwater input) cause about the same

amount of cooling. Note, however, that for the northernmost core site (MD95-2010), Govin et al. (2012) find a warming due to freshwater input. In contrast, we expect cooling at all core locations at around 130 ka due to reduced GHGs. Govin et al. (2012) report that high northern latitude warming is a common feature simulated in freshwater experiments. However, in an independent freshwater simulation by Holden et al. (2010), a high northern latitude cooling of up to ~1°C is found. Unfortunately, the proxy record (MD95-2010) does not extend this far back in time, so we cannot use this data to confirm or discard either scenario. However for the other three core sites, it is likely that a combination of reduced GHGs and freshwater forcing are important for cooling the sea surface.
We will include this discussion in Section 3.2 of the revised manuscript.

Referee #1: *4458.19 The model-data fit of the peak LIG warmth as shown in Figure 4 is quite fascinating in the sense that at site CH69-K09 the simulated August and September temperature maximum is indeed later in comparison to the other sites, in good agreement with the temperature reconstructions. However, according to figure 5 this might well be strongly linked to the fact that this core site is located in the 'feature' described by the authors on lines 4458.16-21. In my opinion it is because of this importance for the model-data comparison that this feature should be explained and discussed more thoroughly because it raises many questions like: How do the authors know that it is a expansion of the subpolar gyre that causes the temperature change? What causes this expansion of the subpolar gyre? If the separation of cold and warm water is shifted southeast, wouldn't you expect both a cooling and warming signal instead of only a clear regional cooling? Is the change in gyre configuration connected to changes in the AMOC? How model dependent is the simulated change in the subpolar gyre and therewith the good model-data fit? Is there other proxy-based evidence for such subpolar gyre changes? How do the changes relate to the inflow of warm water into the Nordic Seas?*
We will include a new figure showing the changes in the subpolar gyre, as given by the horizontal streamfunction, between experiments 130 ka_Gpi and PI on top of the corresponding SST anomalies (see figure below). This figure shows the expansion of the subpolar gyre to the southeast, expanding the area within the gyre with relatively cold SSTs. The other early LIG time slices (125 ka_Gpi, 125 ka and 130 ka) show the same feature. In contrast, in experiments 115 ka and 120 ka there is no significant change in the structure of the subpolar gyre as compared to the PI experiment.
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. Note that an expansion of the subpolar gyre does not require a dipolar SST structure, and that the influence on the North Atlantic drift is minor as the strength of the gyre does not change significantly.



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 #1: *4459.14-28 The authors describe peak summer and winter warmth over the Southern Ocean and over Antarctica. The simulated early LIG summer peak is intriguing since it appears to be in good agreement with proxy-records but it is different from the results of the model inter-comparison published by Bakker et al. (2013). Assessing in what way and why the simulated temperatures by NorESM are different from previous studies would in my view be a great addition to the manuscript (different model set-up? Forcings? Feedbacks? Analyzing method?).*

The results of Bakker et al. (2013) find in their ensemble mean of 7 different models that changes in the Southern Ocean are not consistent. Therefore they rather focus on the Antarctic continent. In their figure 4, two models (FAMOUS and LOVECLIM) do show an early/earlier January temperature maximum over the Southern Ocean combined with a late maxima over Antarctica. In our simulations with NorESM we also find an early maximum over the Southern Ocean and either a late or early maxima over Antarctica. An important difference between our study and that of Bakker et al. (2013) is that we performed equilibrium runs with a coupled GCM, whereas Bakker et al. (2013) describes transient simulations with simplified climate models (EMICs) and accelerated

GCMs.
These differences will be discussed in Section 3.3 of the revised manuscript.

Referee #1: *4459.23-28 I find this section (and therewith also lines 4461.4-6) somewhat confusing. Please clarify how a negative early LIG summer (DJF) insolation anomaly at high southern latitudes (Figure 1) can result in winter warming and how that in turn can explain the early LIG peak summer temperatures. Doesn't it appear from figure 1 that the positive early LIG spring (SON) anomaly should play a role in explaining the early LIG summer peak warmth at high southern latitudes?*

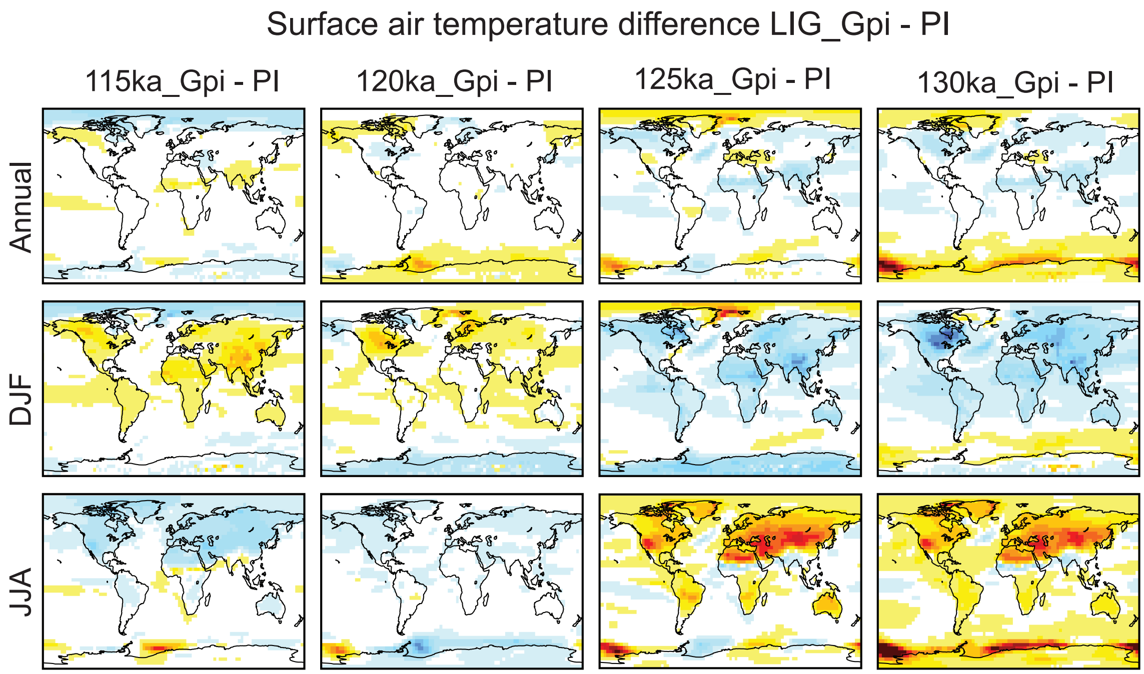
Indeed, the high austral spring insolation (SON) during early LIG causes the Southern Ocean to warm, with a smaller contribution from the relatively weak austral winter (JJA) insolation. The slightly lower-than-PI DJF insolation cannot counteract the JJA insolation (as is done during 125 ka), and the resulting 130 ka ocean temperatures are the highest of the entire LIG.

We will better discuss this in Section 3.3 and conclusions of the revised manuscript.

Referee #1: *Finally, please be more specific on how the processes in the Southern Ocean region feedback on the adjacent land (Antarctica). Related to this, could the authors explain the large high southern latitude temperature difference between ocean and land at 115ka (Figure 6)?*

Figure 6 is difficult to read, therefore we will include a new figure that shows annual, DJF and JJA mean surface air temperature anomaly maps of the four constant GHG LIG time slices (see also below). This figure depicts which regions are warm during the different time slices and in which season. However to compare the time slices to each other and to highlight the timing of maximum warmth we also keep the original figure 6. By normalizing the LIG insolation and temperatures per latitude the timing of peak warmth becomes more clear, and for the real temperature anomaly to PI patterns we will refer to the new figure. As shown in the new figure: there is no large difference between temperatures over the Southern Ocean and over Antarctica in 115 ka. Note that the Southern Ocean warming at 130 ka is amplified by sea ice retreat and thinning, increasing the heat fluxes from the ocean to the atmosphere and enhancing the warming of Antarctica.

We will include this discussion and the new figure in Section 3.1 and 3.3 of the revised manuscript.



New figure #2: Simulated surface air temperature difference between the last interglacial and pre-industrial. Columns show 115, 120, 125 and 130 ka temperature anomalies from the simulations with constant present-day greenhouse gas forcing. Upper row shows annual, middle row shows DJF and bottom row shows JJA mean temperatures.

General questions:

Referee #1: *4456.17 Does this mean that the positive feedback from melting sea ice in summer is stronger than the negative feedback related to winter sea ice growth?*

Yes indeed. Extra sentence will be included.

Referee #1: *4457.25 A reduced inflow of relatively warm Atlantic water into the Nordic Seas is mentioned. But is this found in the simulations? Or in proxy-based reconstructions?*

Sorry, this is not clear in the text. The reduced inflow into the Nordic Seas is a general artifact in NorESM (also found in the PI described in Zhang et al., 2012), not a LIG specific feature. The manuscript will be revised to make this clear.

Referee #1: *Related to the previous question. Bakker et al. (2013) describe large differences in the evolution of the AMOC among different climate models. What are the characteristics of the AMOC in the NorESM simulations and do they change between the different snapshots?*

The AMOC changes slightly between the different snapshots, but not as much as between the different models described by Bakker et al. (2013). Mean value for the PI simulation is 21 Sv, for LIG between 21 and 27 Sv. The higher values are for the early LIG, where the AMOC is also a few hundred meters shallower. A description of AMOC differences will be included in the revised manuscript.

Referee #1: *How does this in turn relate to the changes in Atlantic water inflow and subpolar gyre mentioned in the manuscript?*
The strength of the AMOC for 115 ka is very similar to the PI AMOC, and the subpolar gyre (SPG) is similar in strength and extension. Further back in time the AMOC is stronger and the SPG expands to the southeast. As a consequence the cool patch in the North Atlantic is stronger and more extensive in the early LIG. The strength of the SPG, however, does not change much between the different simulations. This discussion will be included in the revised manuscript.

Referee #1: *On page 4457 Langebroek and Nisancioglu describe a good fit between simulated and reconstructed temperatures. How does this relate to earlier findings by for instance Lunt et al. (2013) who describe an overall poor model-data comparison? Is this difference related to the specific regions chosen in this study? To the types of temperature proxy used in the different studies?*
There are several reasons for the misfit between model results and data found by Lunt et al. (2013). 1) The Turney and Jones (2010) dataset used is extensive and global, and comprises many different types of proxy data. As some proxies record annual mean values and some a certain season, the dataset contains a mixture of annual and seasonal mean temperatures. 2) Also the Turney and Jones (2010) dataset depict local, site-specific maximum temperatures taken from the oxygen isotopic plateau (for ocean sediment and ice cores) or from a period of maximum warmth (for land based proxies). Modeled time slices cannot depict the real extremes found in the data, and the model-data fit is poor. 3) By taking the mean of the entire ensemble any extreme warming (which is captured by the data) is averaged out. Taking only JJA modeled temperatures or warm-month mean improves the misfit indicating that it would be better to compare seasonal model result to the dataset (as also shown by Lunt et al., 2013).
We take this one step further by focusing on the time *evolution* of LIG temperatures, which is a very different approach from Lunt et al. (2013) who investigate the time *mean* LIG temperatures.
These points will be addressed in Section 3.2 of the revised manuscript.

Referee #1: *4460.1-4 Does this finding implicate that including 'more realistic' GHG concentrations in LIG simulations results in a larger disagreement with proxy-reconstructions that show an early LIG temperature peak over Antarctica?*
Yes, this might be the case. However we only compare the maximum temperatures of four time slices. Between 130 and 125 ka the GHG values were lightly higher than today and this result in a short-term (few 1000 years) early maximum, which we cannot detect with our model approach.
We will include this discussion in Section 3.3 of the revised manuscript.

Minor comments: (page.line)

Referee #1: *Abstract: Please make more clear in the abstract what the goal of this research is.*
Will be done.

Referee #1: *4450.7 and 4457.11: On several occasions the authors mention that during the early LIG GHG concentrations were low. This is indeed true for 130ka and, to a lesser extent, 125ka but around 128ka a maximum in CO2 is found (Luthi et al., 2008). Please be more specific.*
We will mention the 128 ka maximum.

Referee #1: *4450.20 'the fit', please be more specific. 4450.22 Clarify why these two are exceptions.*
Will be reworded.

Referee #1: *4450.25 Please specify how relatively warm winters relate to the Southern Ocean austral summer peak temperatures.*
Will be discussed (see also discussion above).

Referee #1: *4451.6 Clarify for the reader what difference it would make if a warming is forced by changes in insolation or GHG concentrations.*
We will clarify this.

Referee #1: *4451.26 The model inter-comparison study by Lunt et al. (2013) includes simulations performed with the NorESM model. Please mention this and clarify if these are the same or that there are differences in the model, in the experimental set-up and or the model results.*
Yes, the same NorESM simulations are use in both publications. Will be mentioned.

Referee #1: *4453.3 and 4453.17 Please look carefully if such details are relevant for this manuscript.*
Yes, we think they are relevant.

Referee #1: *Section 3.1: Please quantify the described changes in insolation and temperature.*
Will be described.

Referee #1: *4455.20-4455.22 I do not see the described evolution of SH insolation in Figure 1. Please clarify.*
Will be better described, maybe we will clarify figure 1 as well.

Referee #1: *4456.2 Global temperatures are mentioned but are these also shown?*
Will be changed to "hemisphere mean temperatures".

Referee #1: *4456.12 this 23 ppm only relates to CO2 and not to GHG in general, please be more specific.*
We will be more specific here.

Referee #1: *4456.22 Discuss the strong SST decrease in most of the cores after 116ka.*
This follows local summer insolation. This will be discussed more (see also above).

Referee #1: *4457.19 It is important to note that this temperature reduction by lower GHG values is valid for 130ka and 125ka but not for 129-128ka, a period with higher GHG concentrations.*
We will mention this.

Referee #1: *4457.27 Please give references for the claim that SSTs can be too high.*
We will better explain/reference this.

Referee #1: *4458.1 For some of the core locations, the model-data comparison reveals a clear bias (as described on 4457.22) but is this bias likely to be explained by the calibration error?*
Partly, but not totally. Note, however, that the NorESM has a cold temperature bias at high northern latitudes in its control simulation.

Referee #1: *4458.5 I would be careful with a reasoning like this because indeed taking into account the uncertainties in simulated and reconstructed temperatures make for a reasonable model-data fit, but wouldn't that also imply that then most any simulated temperature evolution will likely fit to the data?*
True, however in our updated figure 4 we do indicate model and data uncertainties.

Referee #1: *4458.9 Could you provide a reference to this habitat depth issue? Maybe also refer to the recent findings by Lohmann et al. (2013).*
Telford et al. (2013) and Lohmann et al (2013) are included.

Referee #1: *4458.14 Please clarify 'large-scale phenomenon'.*
Will be reworded.

Referee #1: *4459.5 Can the authors explain a bit more what they used as*

reference values and how the mean variations have been calculated?
Will be explained.

Referee #1: *4459.12 This 'slightly earlier maximum (120ka)' is not easy to see in Figure 6.*
Will be reworded.

Referee #1: *4459.13 In this section the peak summer warmth is described for different regions but I think the authors should make it more clear that there are actually large differences between the different summer months as is illustrated by Figure 4 (see also the main concern about section 3.2).*
An extra section discussing this will be included.

Referee #1: *4459.14 Such a late winter peak is not found over the high northern latitude oceans according to Figure 6.*
True, this will be reworded.

Referee #1: *4460.21 Maybe specify which month instead of 'summer' since the difference between the different summer months appear large.*
Will be better specified.

Referee #1: Figure 2: *Why have absolute temperatures been used in figures 2 and 4 and temperature anomalies in figures 3 and 5?*
For figures 1, 3 and 5 anomalies are needed to clarify the differences. Figure 2 could be shown either using anomalies to PI or the direct values. By updating the figure also indicating the PI values, it is more consistent with figure 3 and 5. Figure 4 needs to show the real values as one of the points is to show the offset between modeled and proxy temperatures in the Northern two cores. This offset will be much smaller when plotting the anomalies.

Referee #1: *Figure 4: I find the lines representing the simulated temperatures somewhat misleading since they represent only 4 'dots' based on the snapshot simulations. Maybe show both the actual dots and the lines? Maybe for both the data and the simulations present-day or pre-industrial reference values can be depicted to clarify for the reader if temperatures were above or below present-day.*
Dots and pre-industrial values are included (see also updated figure 4 above).

Referee #1: *Figure 6: The colour coding and the applied normalization procedure nicely show high and low temperatures and insolation values. However, it appears that the normalization has also caused in a number of occasions the sign to change. For instance, DJF 130ka insolation at high southern latitudes appears positive in Figure 6 but negative in Figure 1. I do not think that a normalization procedure should make values change sign. Another somewhat* *strange feature is the monotonic southward increase in JJA insolation for 130ka depicted in Figure 6 which is rather different from Figure 1 showing an increase from 90N to the equator and then a decrease towards 90S.*

The normalization is applied per latitude band, therefore latitudes cannot be compared to each other. The apparent monotonic southward increase in JJA insolation for 130 ka is therefore not real. We will include a new figure showing temperature maps (see new figure above). Also, the normalization is applied on the LIG temperature values itself, not on the anomalies to pre-industrial, so a negative value does not imply lower than PI values, but rather lower temperatures compared to the other LIG time slices.

We will include a better description and a new figure (see above) in the revised manuscript.

Technical comments: (page.line)

Referee #1:

- *Be consistent with using abbreviations throughout the text. If the LIG is introduced on 4450.2 and 4451.2 then use it in the remainder of the text. The same holds for instance for 'GHG'.*
- *Often the word 'our' is used but perhaps it is better to use a more general formulation.*
- *4450.10 'in two simulations additionally GHG forcing was', please rephrase this sentence.*
- *4450.14 'compare our modelled results', please rephrase this sentence.*
- *4450.16 'Our modelled', please rephrase this sentence.*
- *4450.17 'trend of the proxy summer temperatures', maybe use 'reconstructed' summer temperatures.*
- *4450.19 'computed by the simulations', please rephrase.*
- *4450.22 'follows', maybe use 'is in line with'.*
- *4451.4 Not sure if the plural form should be used here. Maybe use 'by a warm high latitude climate'.*
- *4451.13 Please rephrase.*
- *4453.25 LIG already mentioned.*
- *4454.1 mentioning 'atmospheric greenhouse gas concentrations' and 'CO_2, CH_4 and N_2O' seems a bit redundant.*
- *4454.10 130 ka, respectively.*
- *4454.15 '(from model year 495 to 1000)' is maybe a bit too specific.*
- *4454.15 'new', maybe reword.*
- *4454.23 Reverse order in 115-130.*
- *4455.19 and 4455.24 and 4456.4. Perhaps it is confusing for the reader that the meaning of 'late LIG' is not consistent throughout the text.*
- *Figure 4: Perhaps use Reconstructed and modelled instead of proxy and modelled in the figure caption.*

All technical comments will be applied in the revised manuscript.

References:

Holden, P.B., Edwards, N.R., Wolff, E.W, Lang, N.J., Singarayer, J.S., Valdes, P.J., and Stocker, T.F.: Interhemispheric coupling, the West Antarctic Ice Sheet and warm Antarctic interglacials, Clim. Past, 6, 431-443, 2010.

Lohmann, G., Pfeiffer, M., Laepple, T., Leduc, G., and Kim, J.-H.: A model–data comparison of the Holocene global sea surface temperature evolution, Clim. Past, 9, 1807-1839, doi:10.5194/cp-9-1807-2013, 2013.

Telford, R. J. Li, C., and Kucera M.: Mismatch between the depth habitat of planktonic foraminifera and the calibration depth of SST transfer functions may bias reconstructions, Clim. Past, 9, 859–870, 2013.