Response to Pepijn Bakker

We would like to thank the reviewer for his comments and suggestions that will guide our revisions and improve this paper. We hope that the revisions we plan to implement should satisfactorily address his comments.
Below, the reviewers' comments are highlighted in italic, and our responses follow in blue.

Marie Sicard on behalf of the co-authors

The manuscript presents a thorough analysis of the changes in the Arctic climate simulated for the LIG. By doing so they manage to pinpoint the causes of the changes. The manuscript is well written and the authors have managed well to ensure that it reads well despite the lengthy and technical results. In the following I will list my comments and suggestions.

Main comments:

On lines 157-158 'similar behavior' is mentioned when it comes to simulating the LIG climate with the IPSL-CM6A-LR model or with the PMIP4 models presented by Otto-Bliesner et al. (2021). This is an important statement because it would imply that the results presented in this manuscript are more widely applicable to the PMIP4 LIG simulations. First of all, it should be made more clear in the manuscript what is meant with 'similar behavior'. Moreover, when looking at temperature and sea-ice changes for the PMIP4 ensemble in Otto-Bliesner et al. (2021), I see large differences. The magnitude of JJA and SON sea-ice anomalies varies widely and for winter (DJF) models even differ in the sign of the sea-ice anomalies. I think a short summary of the findings of Otto-Bliesner et al. (2021) related to sea-ice and the Arctic is needed in the current manuscript to put the results and analysis of the IPSL-CM6A-LR model in perspective.

The reviewer is right. We agree that the term "similar behaviour" is confusing. Here, "similar behaviour" refers to the common feature shared by PMIP4 models to reproduce near-surface temperature anomaly suggested by the temperature synthesis provided by *Otto-Bliesner et al., 2021*. We propose to remove the following sentence:
"Despite model-data disagreements, the IPSL-CM6A-LR model and most of the models considered in *Otto-Bliesner et al. (2021)* converge towards a similar behaviour."

In order to put in perspective, the results of the IPSL-CM6A-LR model with those of other PMIP4 models, we propose to add these few lines at the end of section 4:
"*Otto-Bliesner et al. (2021)* have highlighted the large differences in the magnitude of high latitudes near-surface temperature anomalies among PMIP4 climate models that have run the lig127k simulation. On an annual scale, Arctic near-surface temperature changes range from -0.39 to 3.88°C. Models that simulate the most intense surface warming also show the largest reductions in minimum Arctic sea ice area (*Kageyama et al., 2021*; *Otto-Bliesner et al., 2021*). There is a large spread across models for the simulated summer Arctic sea ice area, with minimum sea ice area anomalies ranging from 0.22 to 7.47 x 10^6 km^2 for the Last Interglacial. Moreover, there is no consensus about the sign of winter sea ice area variations, with three models simulating a decrease in sea ice area during this season.

Furthermore, the effective climate sensitivity (ECS) of PMIP4 models varies from 1.8 to 5.6°C (Otto-Bliesner et al.,2021). The IPSL-CM6A-LR model is in the higher range with an ECS value of 4.6°C. However, this model does not simulate a strong annual Arctic warming and a large summer Arctic sea ice retreat compared to other models with high ECS values such as EC-Earth3-LR (4.2°C) or HadGEM3 (5.6°C)."

Related to the comments above, I have a further comment on the role of clouds, the difficulty to model them and the 'robust' PMIP results for the LIG. A large role is determined here for the radiative effects of clouds. The role of clouds in the climate system is one of the things that are generally seen as very uncertain in models, so it seems surprising that PMIP3/4 models would show similar cloud effects for the Arctic in the LIG. How does one reconcile that? Does it imply that certain cloud feedbacks are in fact quite robust in models?

Low-level clouds strongly impact the Arctic energy budget, primarily through their effects on incident solar radiation at the surface (SWdn). As shown in Kageyama et al. (2021), while the insolation received at the top of the atmosphere is similar for all models following the PMIP4 lig127k protocol, the amplitude of the SWdn annual cycle anomaly varies across PMIP4 models. The atmospheric energy budget could be analysed for only eight models (out of the initial 17 models), for which the data was available. Even with this reduced data set, the diversity of responses suggests that cloud feedbacks are not consistent in these climate models.

This information will be added to section 4.

Minor comments:

As we know, the LIG is not a direct analogue for the future. Most importantly, insolation in winter was lower, quite different from ongoing and future CO2-driven warming. However, this study suggest that it is mostly the summer and autumn seasons that determine the differences in the Arctic climate compared to PI. Does that mean that in this specific context, the LIG does provide a rather good analogue? Can such a statement be made?

From this study, it is difficult to conclude whether the Last Interglacial provides a rather good analogue for the future Arctic warming because we do not directly compare the Last Interglacial and future Arctic energy budgets simulated by the IPSL-CM6A-LR model. Based on future climate projections, near-surface air temperatures are expected to rise in the Arctic throughout the year with a maximum anomaly relative to the pre-industrial period reached in winter. The annual evolution of the near-surface air temperature anomaly is different at 127 ka due to the seasonality of the insolation forcing: we have shown that Arctic climate warms in summer and autumn but cools slightly in winter and spring. Regarding mechanisms and feedbacks driving the Arctic warming, we can expect that longwave radiation plays a greater part in future Arctic amplification compared to the Last Interglacial due to the increased greenhouse gases forcing. This will actually be the topic of further work, which is not fully finalised at the moment.

It seems that in Otto-Bliesner et al. (2021), the winter sea-ice area is increasing for the IPSL-CM6A-LR model while in the current manuscript a decrease is presented. Please clarify this difference.

Yes, this is due to our definition of the Arctic region. We have averaged sea ice area between 60 and 90°N, thus excluding regions where sea ice anomalies are positive in winter i.e. south of Greenland and in the Sea of Okhotsk (fig. 7e).

Lines 108-114: two phases of the lig127k experiment are mentioned, one 350 years long and another one 550 years long. What is the difference between these two? Try to explain this more clearly.

We modified the text as follow:
"The model was first run for 350 years. This initial step constitutes the spin-up period, during which the model reaches a statistical equilibrium under the Last Interglacial forcing. The final state of this spin-up phase is used to initialise the reference PMIP4-CMIP6 *lig127k* simulation which has been run for 550 years. The last 50 years have been produced saving high-frequency outputs for the analyses of extremes or to provide the boundary conditions for future regional simulations."

Lines 153-156: a cold bias over Greenland in the PI simulation does not need to correspond to a too small temperature increase due to the 127k forcings. The relationship between biases in the present-day climate and the response of a model to a given forcing is often far from straightforward. The authors nicely show and discuss this in the discussion section, but these lines seem to indicate otherwise. Please clarify.

We fully agree with the reviewer and propose to remove the following sentences, since this is a topic which we go back to in the discussion section:
"This bias has already been identified in the evaluation of the IPSL-CM6A-LR present day climate. It could be slightly amplified by the prescription of a modern Greenland ice sheet in the LIG simulation."

Lines 226-227: The authors mention that the drift in deep ocean temperatures are not negligible, however, they are not discussed at any point later in the manuscript. Please clarify.

We did mention a drift in deep ocean temperatures, in order to explain the fact that the annual mean value of ocean heat storage is not zero. Figure 5 shows that indeed there is a small drift in ocean heat content. However, this figure was somewhat misleading because of the chosen vertical scale, and the fact that the regression was computed on the whole simulation. We propose to replace Figure 5 by the figure below, which shows that during the first 300 years, the ocean heat content undergoes significant oscillations, which decrease in amplitude during the last 200 years of the simulation, which are analysed in the present work. The trend computed over these last 200 years is small, but because of small oscillations in ocean heat content, it is nonetheless important to keep the last 200 years for the analysis. In fact, we do not discuss the influence of such a drift because we are mostly interested in changes in the upper layers of the ocean where air-sea exchanges take place. Figure 8 shows that the major oceanic temperature variations occur in the first 60 m of the ocean and do not reach the deepest layer of the ocean due to ocean stratification.

We therefore propose to replace the paragraph including lines 226-227 by the following text:
"The annual value of storage terms should be zero in the ideal case of an equilibrium climate. This is not the case for both simulations. The PI AHS and OHS are lower than the current observed energy imbalance of 0.5 W m−2 in terms of absolute value (*Roemmich et al., 2015*; *Hobbs et al., 2016*). However, the LIG AHS and more specifically the LIG OHS are far above this reference value since they are respectively equal to 0.5 and 1.1 W m−2. This "energy excess" may arise from assumptions made for the energy budget computation or from an ocean drift in the LIG simulation. Figure 5 shows that the SST and ocean heat content drifts are small over the last 200 years of the simulations."

Since most of the changes of interest later in our study occur in the first 60 metres of the ocean (cf. Fig. 8), we do not discuss these drifts further.

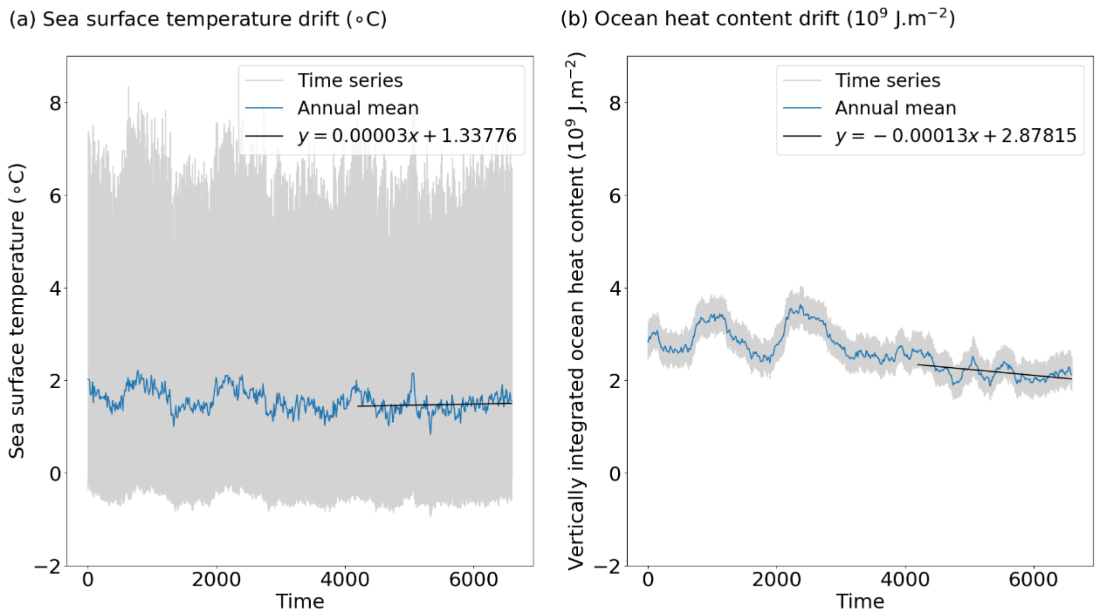

Figure 1 : Time series of (a) the sea surface temperature (∘C) and (b) the vertically integrated ocean heat content (J m^{-2}) averaged over the Arctic region (60–90°N). The time axis indicates the number of months since the year 1850. The black lines show the results of linear regressions over the last 200 years of the simulation.

Line 239: Are these atmospheric surface air temperatures, SSTs? Please clarify.

These are near-surface air temperatures. This has been corrected.

Line 242: Comparing the simulated Arctic LIG warming with other PMIP3/4 models seems more relevant then global means in light of the topic of this manuscript.

We agree with this comment and we modified the text as follows:
"Change in insolation between the LIG and the PI periods leads to ~~a global mean annual anomaly of –0.19°C. This value is in the range of the PMIP3 multi-model mean estimate of 0.0 ± 0.5°C (*Masson-Delmotte et al. 2013*) and close to the PMIP4 multi-model mean value of –0.02 ± 0.32°C (*Otto-Bliesner et al., 2021*). In the Arctic region, the temperature response to orbital forcing results in a mean annual warming of 1.8°C compared to PI.~~ an annual Arctic near-surface air temperature anomaly of 0.9°C. This value is in the range of the PMIP4 multi-model mean of 0.82 ± 1.20°C (*Otto-Bliesner et al., 2021*)."

Note that we made a mistake line 242: the annual Arctic near-surface air temperature anomaly is 0.9°C compared to PI and not 1.8°C.

Lines 253-255: Clarify if these are regional, ocean or continental averages.

Here, these are regional averages. We will modify the text accordingly.

Technical comments:

We thank the reviewer for his corrections. We will take them into account and correct the text accordingly.

Line 14: radiation instead of radiations
We replaced "radiations" with "radiation" whenever this term appears in the text.

Lines 26 and 28: too many brackets?
Yes, this is now corrected.

Line 46: another instead of an other
We replaced "an other" with "another".

Line 98: check brackets
We removed the extra parenthesis.

Line 119: To prevent such so-called "paleo-calendar effects"….
We modified the text accordingly.

Line 123: cloud
We replaced "clouds" with "cloud".

Line 141: but it does not reproduce

Line 153: saptial is spatial?
This is a typing error. We replaced "*saptial*" with "spatial".

Line 266: One bracket too many
We removed the extra parenthesis.

Line 271: Be careful with the usage of 'near surface air', 'surface air', these things normally have different meanings. Clarify ones what you mean with it and consistently use the term thereafter.
As we use t2m-temperature we will use near-surface air temperature hereafter.

Line 306: is advected way from the Arctic basin; or advect out of the Arctic basin
We replaced "is advected outside the Arctic basin to balance" with "is advecetd way from of the Arctic basin".

Figures 4 & 5: clarify if these results are for the PI or LIG simulations.
Figure 4, results are for the pre-industrial period. Figure 5, results are for the Last Interglacial. We modified the caption accordingly.

Figure 4: "Annual zonal mean northward heat transport (PW) for the pre-industrial period. The northward heat transported computed as residual are represented by a solid line. The atmospheric heat transport is in black and the oceanic transport is in blue. The oceanic heat transport simulated by the IPSL-CM6A-LR model is represented by the dashed blue line."

Figure 5: "Time series of (a) the sea surface temperature (°C) and (b) the vertically integrated ocean heat content (J m^{-2}) averaged over the Arctic region (60-90°N) for the Last Interglacial. The time axis indicates the number of months since the year 1850."

Figure 8: these are all temperature anomalies?
Yes. The first panel represents the atmospheric temperature anomaly. The second one shows the oceanic temperature anomaly.

References:

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