Reply for anonymous reviewer #1 of PMIP4 experiments using MIROC-ES2L Earth System Model

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Thank you, the anonymous reviewer, for the thought-provoking and constructive comments. In the following reply, the reviewer's comments are written in black texts and our responses are in bold and blue texts.

The paper summarizes PMIP4 experiments using the Model for Interdisciplinary Research on Climate Earth System Model (MIROC-ES2L). Experiments for PI, LGM, interglacials (6k, 127k), LM and historical are presented. The MIROC-ES2L is an ESM developed for CMIP6 (Tatebe et al. 2018, Scientific Reports; Hajima et al. 2020, GMD), but the version has more ESM components like the ecosystem, aerosol and vegetation modules. Most analyses are however related to the more standard physical quantities like SAT, precipitation, and ocean circulation (AMOC). The paper needs some revisions before publication, somehow in between minor and major revisions. Part of the analysis is not very deep and a little speculative, some innovative aspects of the new model as the ocean biogeochemical model OECO2 are not considered in detail. A positive aspect of the paper is the compilation of different PMIP experiments in one paper. The evaluation of the climate sensitivity is not mentioned.

More earth system analysis has been augmented such as discussions on biogeochemical cycles at LGM, and revisions have been made to the text. In Addition, because we realized many modelling groups have difficulty in conducting LGM experiment, we added Appendix describing the most difficulty we encountered during the spin-up of the LGM experiment. Climate sensitivity has also been mentioned in Introduction, Sect. 2 and Sect. 5. We will respond to each comment below.

1) page 2, line 46, Because cooling at LGM relative to PI is at a comparable level to present-day global warming, -this statement is not valid. The present day warming with respect to PI is in the order of 0.5-1 K, the cooling LGM-PI is in the order of 3 K, regionally much larger (e.g. 10 K or more)

"Present-day global warming" was misleading; this is a comparison between ECS and LGM-PI.
These changes do not have to match exactly, but it is better to have some large changes in the recent past where the ocean-land distribution does not change much from the present

day, which can be used to constrain the ECS (Annan et al. 2005, Renoult et al. 2020). We discussed this in the text.

2) page 3, line 68, However, models have been unable to reproduce the quantitative changes recorded in proxy data. -Please provide a reference. This statement is not very specific. Please modify and be explicit saying which type of paleoclimate data you are refering to.

We added McKay et al., 2011, Capron et al., 2014, Hoffman et al., 2017 in the manuscript.

3) page 4, SECTIONS 3.2 and 3.3 setup and spin-up: -Specify how you treat the PFTS. It is not mentioned in the text, but shown in Fig. 4
4) page 8, line 252 We prescribed conventional land PFTs in the LGM experiment. -This is not clear. The reader thinks that all experiments work with prescribed PFTs.

As you pointed out, the explanation of the PFTs was insufficient. We have added the following explanation to text in Sect 3.1.
"The PFTs in PI are inherited from MIROC-ESM (Watanabe et al. 2011), which was based on Ramankutty and Foley (1999). "
The definition of the PFTs of LGM is also described in Sect 3.2 as follows.
"The LGM PFTs were created on the PI PFTs with the ice sheet grids defined by ICE-6G_C, and nearby PFTs were diverted to non-ice sheet land (exposed continental shelves) that expanded from PI.", "The erodibility map specifies low latitudes as deserts and mid- to high latitudes as tundra"

5) The language needs some improvements.

Language was improved by a professional language reviewer.

6) page 7, line 199: calculated for June to August (JJA) and December to 200 February (DJF). -Please discuss the seasonality issue for past climates. Similar isse in Fig. 12: Please correct for the paleo-calendar (e.g. following Braconnot)

Calendar adjustments were introduced to LGM, 6ka, and 127ka, and the related figures were replaced.

7) page 8, line 223: There is also good agreement between HadCRUT4 data and output from all of the historical experiments at the multi-decadal time scale. -Be more specific, "good agreement" can be substanciated

After submitting this manuscript, we expanded the historical experiments for CMIP6, up to 30 ensemble members. The CMIP6 standard historical experiments were removed from Figure 13(a) because it is difficult to identify. Figure 13 (b) shows the HIST experiment starting from 1850 with standard 30 members and comparison with HadCRUT4, and (c) shows the histogram of biases from HadCRUT4 for the period from the late 19th century until the first half of the 20th century. The results showed that the HIST showed less positive bias than the standard historical experiments.

8) page 8, line 237 This could be attributed to a strong AMOC in the models, which leads to an estimate of sea ice expansion over the northern Atlantic Ocean that is lower than that suggested by proxy data. -a strong AMOC would reduce the sea ice? please comment

Correlation between strong AMOC and sea ice retreat has been reported from observation and modelling studies (Boehm et al. 2015, Peltier and Vettretti, 2014). This has been added to the text.

9) page 8, line 240 Positive SST bias over the Southern Ocean in the model at PI may also contribute towards the underestimation of abyssal flow and could result in a persistently strong AMOC at LGM. -too speculative, please substanciate your statement

As you pointed out, the statement was too speculative. It was changed as follows.

"Insufficient abyssal flow into the Atlantic Basin could be partly caused by the low resolution of the ocean component. Detailed analyses on the representation of atmospheric circulations would be necessary for further investigation. Model representation of the Southern Ocean might influence the distribution of CO_2 between the atmosphere and the ocean (Moore et al., 2000). Anomalies associated with topography might be obscured by the low horizontal resolution of the model, resulting in discrepancies between climate states in the model and those derived from proxy data. Cooling of Eastern Antarctica during the LGM relative to PI, which is suggested by ice core data (−7 to −10 °C), is underestimated by this model (−6 °C), as explained in Sect. 4.2. This could be partly attributed to the positive SST bias over the Southern Ocean in the model at PI and subsequent underestimation of sea ice expansion. PMIP model analyses (Otto-Bliesner et al. 2007, Marozzochi and Jansen 2017) also suggested the correlation of AMOC and sea ice coverage."

10) page 8, line 245 Cooling of Eastern Antarctica at LGM relative to PI that is suggested by

ice core data is underestimated by the model. -please provide references and numbers.

We rewrote as follows,
Cooling of Eastern Antarctica at LGM relative to PI that is suggested by ice core data (-7 to -10 degree C (Stenni et al. 2010, Uemura 2012) is underestimated by the model (-5.1 degree C).

11) page 9, line 263 This is consistent with the direction of change suggested by proxy archives (Bartlein et al., 2011; Turney and Jones, 2010) -Be aware of the proxy for temperature during LIG, it is related to peak interglacial conditions. See e.g. Pfeiffer and Lohmann (2016, CP) for a discussion on that.

The following has been added to the text.
Pfeiffer and Lohmann 2016 suggested that we need to take into account the uncertainty of the times of the proxy data.

12) page 9, line 269 the degree of improvement would be area dependent. -please be more specific, too vague

Rewritten as follows. "The vegetation coupling greatly improves the representation of the warmings shown by proxies at the Arctic Ocean margin (O'ishi and Abe-Ouchi, 2011, **O'ishi et al. in press CP). On the other hand, some inconsistency remains in inland areas such as inner Eurasia."**

13) page 9, line 269 Compared with PI, temperature over the tropics is lower in the 6ka experiment, which contradicts with proxy data. -This is not correct, see, e.g. Lohmann et al. (2013, CP) for the SST data and modeldata comparisons

Thank you for letting us know Lohmann et al. (2013, CP). We changed the description to "Compared with PI, temperature over the tropics is lower in the 6ka experiment, which is in the range of variability of the proxy data (Bartlein et al. 2011, Lohmann et al. 2013). ".

14) page 24, line 674, peak values of annual mean AMOC. -please exclude the surface layers since they reflect the wind-driven part. In several papers, the upper 300 m (or similar) are excluded.

The peak value between 15 - 60 N and between 950-3300 m was taken as the peak value

of AMOC in the analyses. This is described at the end of Sect 4.1 in the text.

15) page 25, caption of Fig 5: -the colors are partly difficult to identify, e.g. light blue.

We put numbers in the figure to identify each experiment, and described them in the caption.

16) LGM: in the paper, please mention the potential bias due to the choice of initial condition. E.g. the deep ocean salinity structure is quite different from the modern one. It shall be mentioned that the spin up procedure, the initial condition, and the limited sin up time of less that 2000 years might be related to this mismatch.

The LGM spin-up was integrated for 6760 years using the physical core AOGCM to take longer, as described in Sect. 3.2, and 2200 years after adding the giogeochemical modulus (Figs. 4, 5). That is, we submitted 100 years after a total of 8960 years of spin-up as a physical field for temperature, salinity, etc. to CMIP6/PMIP4. This is sufficiently longer than the length of the deep ocean circulation.
The distribution of salinity and ocean temperature, as you pointed out, was also added to Supplemental Fig. S2 and described in text Sect. 4.2 , 4.3 and discussed in Sect. 5.

17) page 25, AMOC plots: the figures shall be improved by inserting the minimum ocean depth (e.g. in grey)

We leave the figures as they are because the minimum ocean depth of the model is 1 m, it cannot be resolved in the figures of full ocean depth.

18) Figure 10: Indeed a week precipitation response in the tropics and subtropics. Is the zonal water vapor transport too small ?

The zonal water vapor transport is shown in Supplemental Fig. S1. The results show an overall decrease in water vapor transport in the PI. This is described in Sect. 4.2.

19) Please mention the model's climate (or ES) sensitivity in the paper.

ECS of MIROC-ES2L is 2.66. The relation between paleoclimate and climate sensitivity is added in the Introduction and the value is described in Sect. 2. Discussions are added in Sect 5.