Reply to
1st Reviewer

Dear referee,

thank you very much for accepting to review our manuscript and for the time you dedicated to its revision.

Below we go point by point through your technical corrections, presented in *italic*, detailing how we dealt with your concerns reported in **bold**.

Sincerely,

Emmanuele Russo on behalf of the author team

Main Comments

Recommendation: The manuscript is, in my opinion, well and clearly written, but the motivation of the study does not come across as clearly. I have some recommendations that the authors may want to consider in a revised version

- *The research question and motivations of the study are somewhat unclear. The study presents a new set of simulations, but why are they necessary? What were the deficiencies of previous simulations? Why is a convection-permitting resolution in principle necessary to better simulate the climate of the LGM? One of the main conclusions is that the resolving convection does have a clear effect on the simulated precipitation, but it remains unclear - unless I missed it in the manuscript - whether the convection scheme improves the simulation of precipitation (and maybe temperature) compared to the reconstructions.*

We agree with the reviewer that the motivations of the study are somewhat unclear in the previous version of the manuscript. The paper aims at evaluating a set of new simulations of the LGM climate over Europe and the Alpine region, using an updated version of the WRF model 3.8.1 employed in previous studies. The

updated model version includes some important bug corrections relative to the representation of ice processes in the soil as well as the introduction of a new orbital parameters routine, both of significance importance for the study of glacial times. From this point of view, the outcomes are relevant for updating previous results and for people aiming to perform new simulations for glacial periods with the same model version. At the same time, the paper considers a series of different uncertainties in the model experimental setup, showing where the results of an RCM are likely to be more uncertain for the considered case study, and for which variable, also relevant for future studies. Additionally, the produced high-resolution model outputs were initially designed to be used for simulating glaciers over the Alpine region at the LGM (Jouvet et al. [2023]). We will make all these points clearer in the new version of the manuscript. As for the role of explicitly solving convection on the simulation of the LGM European climate, in the paper we show that this could have important implications on model results, with an effect on both temperature and precipitation comparable in some case to the one of other changes in the model setup, such as modified continental ice height. This is in our opinion a very important outcome of the paper and we will try to better highlight this point in the new version of the manuscript. We also want to emphasize here that the goal of our analysis in this respect is to assess the role of convection-permitting resolutions, comparing it with other sources of uncertainty, rather than quantifying their added value for paleoclimate studies. In fact, we think that the small number of available proxy records and the relatively large size of their uncertainties would make it difficult to assess the added value of convection-permitting simulations for this case study with any statistical significance. While we do not plan to conduct additional analyses in this respect, acknowledging the referee's comment, we will expand the text on this subject to provide a more comprehensive discussion in the new version of the manuscript.

- *The model set-up also includes a small ensemble with different initial conditions (?). The study finds that the ensemble spread can be large for precipitation, but not so much for temperature. However, the length of the simulations is short, just 11 years. Is it possible that* *the ensemble spread is just due to the short length of the simulations? Could this spread be compared to the decadal variability of precipitation in the present climate?*

Following the referee's comment, we realised that the current description of the proposed experiments is not very clear and we propose to modify it accordingly in the new version of the manuscript. The ensemble is actually not generated with different initial conditions, but with different boundaries and surface forcing. We will better specify this in the new version of the manuscript. We additionally understand the concern of the referee about the short length of each simulation for the calculation of climatological values of both temperature and precipitation. For this reason, also following a comment from the 2nd referee, we calculate here as an example the maximum range of differences in JJA temperatures between 20 different 10-year long periods derived from the 31-year long LGM simulation of Velasquez et al. 2021. Fig. 1 shows that the ensemble spread in this case is rarely exceeding 2K, compared to maximum differences of up to 14K obtained in the case of the 5-member ensemble with different boundaries presented in our paper (Fig. 5 and Fig. 6 of the former manuscript version). This suggests that even though some differences between the different ensemble members with changes in the model setup may originate from the consideration of a relatively short period of 10-year used for calculating climatological values, the presented results suggest that the large ensemble spread is not attributable to the short length of the simulations. We will take care to properly discuss this point as well as adding the new figure in the new version of the manuscript.

Specific Comments

'However, these increases in model complexity have not generally led to improved model performance when compared against proxy ...'. Could the authors be more specific here? What are the deficiencies of previous simulations that remain unexplained?

Here, we wanted to refer to the results of Kageyama et al. [2021]: "Therefore, although there are differences in the average behaviour

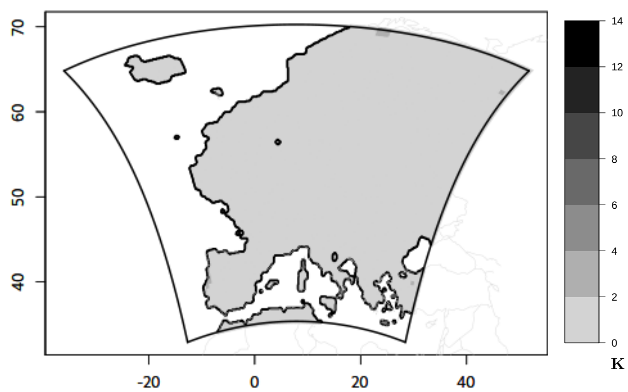

Figure 1: Maximum range of differences between the climatological values of JJA 2-meter temperature derived from 20 10-year long periods sampled from the 31-year long simulation of Velasquez et al. 2021.

across the two ensembles, the new simulation results are not fundamentally different from the PMIP3- CMIP5 results. Evaluation of large-scale climate features, such as land–sea contrast and polar amplification, confirms that the models capture these well and within the uncertainty of the paleoclimate reconstructions. Nevertheless, regional climate changes are less well simulated: the models underestimate extratropical cooling, particularly in winter, and precipitation changes." Following the referee's comment, we will try to better highlight model deficiencies that still remain unexplained according to the reported reference of Kageyama et al. [2021] in the new version of the manuscript.

- *' Model results are evaluated against a newly developed pollen-based reconstruction database for the European LGM climate.*

  A reference to the new reconstructions would be helpful here.

Thank you. We agree and we will add here the reference to the new reconstruction data set in the new version of the manuscript, as suggested by the referee.

- *The starting point of the presented simulations is the results of earlier studies using the same model version (Velasquez et al., 2020, 2021, 2022).'*

  Same model version? The sentence a bit later in the paragraph says 'previous version'. Could the specific model version used by Velasquez et al. be mentioned here?

Yes, we used the same model version of Velasquez et al. 2020, 2021, 2022. Following the referee's comment, we will revise this part of the introduction accordingly in the new version of the manuscript, also adding the specific model version used by Velasquez et al. 2020 (WRF 3.8.1) whenever necessary.

- *' D01 and D02, down to a spatial resolution of 18 km and with the convection parameterization switched on, is performed. This experiment is indicated as DEF_noconv in Table 3'*

  switched off, I guess.

Following the referee's comment we have realised that the description of the experiment DEF_noconv in the former version of the manuscript is not clear. In the experiment DEF_noconv convection is actually parameterised and not explicitly solved. In this case, the convection scheme is switched on. We will try to make this clearer in the new version of the manuscript, modifying the description of the experiment DEF_noconv accordingly.

- *These differences are in some cases of the same order of the differences between the different ..'*

  ...order of magnitude as the differences between.

Thanks. We agree with the referee and we will modify the highlighted text according to the referee's suggestion.

References

Guillaume Jouvet, Denis Cohen, Emmanuele Russo, Jonathan Buzan, Christoph Raible, Urs Hischer, Wilfried Haeberli, Sarah Kamleitner, Susan Ivy-Ochs, Michael Imhof, Jens Becker, and Angela Landgraf. Coupled climate-glacier modelling of the last glaciation in the alps. *Journal of Glaciology*, 2023.

M. Kageyama, S.P. Harrison, M.L. Kapsch, M. Lofverstrom, J.M. Lora, U. Mikolajewicz, S. Sherriff-Tadano, T. Vadsaria, A. Abe-Ouchi, N. Bouttes, Chandan D., L.J. Gregoire, R.F. Ivanovic, K. Izumi, A.N. LeGrande, F. Lhardy, G. Lohmann, P.A. Morozova, R. Ohgaito, A. Paul, W.R. Peltier, C.J. Poulsen, A. Quiquet, D.M. Roche, X. Shi, J.E. Tierney, P.J. Valdes, E. Volodin, and J. Zhu. The pmip4 last glacial maximum experiments: preliminary results and comparison with the pmip3 simulations. *Climate of the Past*, 17(3):1065–1089, 2021.