Response File – Climate of the Past Manuscript cp-2026-3988

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Title: European seasonal temperature change since the Last Glacial Maximum from climate models

We sincerely thank the reviewers for the time, effort, and thoughtful consideration they devoted to reviewing our manuscript, as well as for their insightful comments and constructive suggestions, which greatly helped improve the quality of this work.

Reviewer comments are shown in *italic*. Our original responses are shown in **bold** and the updated descriptions of how we propose to modify the manuscript are indicated in **bold blue text**. Quotations from the original manuscript are shown in ***bold italics*** and quotations from the proposed manuscript are shown in ***bold blue italics***.

Reviewer #1: RC1: 'Comment on egusphere-2026-3988', Anonymous Referee #1, 07 Sept. 2026

Major Comments:

1. The manuscript discusses both inter-model differences across the ensemble and the distinctive response of iLOVECLIM relative to the GCMs. These questions are closely related, but not fully equivalent. The sensitivity experiments provide useful insight into processes that may contribute to the iLOVECLIM–GCM discrepancy, but it is less clear whether the same processes explain the spread among the GCMs.

I therefore suggest making this distinction clearer in the Introduction, Section 4, and Conclusion, and framing the iLOVECLIM experiments primarily as a mechanistic exploration of its distinctive response.

We fully agree with the reviewer's comment. Our sensitivity experiments with iLOVECLIM do not, by themselves, explain the inter-model spread in simulated changes in temperature seasonality over Europe since the LGM. Given that each model differs in terms of numerical scheme, spatial discretization, and representation of physical processes, the spread among the GCMs in simulated European temperature seasonality changes appears to be larger than the distinction between iLOVECLIM and the GCMs (Figs.1 & 3 of the submitted manuscript).

Considering the substantial computational cost of GCM experiments, our iLOVECLIM sensitivity experiments are intended to go beyond a comparison of model outputs by providing a mechanistic exploration of the contribution of individual climate processes to the LGM European climate simulated by iLOVECLIM, and thereby helping to identify processes that may contribute to its differences from the other GCMs. A process-based interpretation of the inter-model spread across GCMs would require dedicated ensembles of model configurations in which the representation of individual processes is systematically varied while keeping the spatial resolution identical.

The specific question addressed by these experiments is therefore not which processes explain the inter-model spread among the GCMs, but rather: which processes in iLOVECLIM

increase the amplitude of temperature seasonality at the LGM relative to the PI, within and around the Fennoscandian Ice Sheet (FIS), thereby bringing the iLOVECLIM response closer to the range simulated by the GCM ensemble? In the absence of sufficient seasonal LGM observations over Europe, this approach requires us to quantify the seasonal biases in iLOVECLIM by comparing its spatial patterns with those simulated by the GCM ensemble.

In this context, it is important to distinguish between the changes in MTWA and MTCO used to estimate changes in temperature seasonality. Based on the results presented in Section 3.2, the candidate processes responsible for the differences between iLOVECLIM and the GCMs preferentially affect winter temperatures at the LGM within and around the FIS, while leaving the changes in MTWA relatively unchanged. Among the sensitivity experiments, the IRN experiment is the only one that produces a response consistent with this mechanism.

We have therefore revised the Introduction, Section 4, and Conclusion to make this distinction clearer and to explicitly frame the iLOVECLIM sensitivity experiments primarily as a mechanistic exploration of its distinctive response, rather than as an explanation of the inter-model spread among models. Several corrections have been applied:

In introduction
"In Sec. 4, we evaluate the impact of several physical processes in iLOVECLIM on the simulated temperature change in seasonality at the LGM, and compare the results with those from the GCM ensemble." In line 131-133.

In section 4
"Moreover, although LGM MTCO values differ substantially among models (Fig.S5), they are broadly similar among different configurations of the same model generation, as illustrated by the three iLOVECLIM versions, motivating the process-based sensitivity experiments presented in Sec. 4." In line 515-518.

In conclusion
"We show that, despite a substantial inter-model spread (STD of up to 12°C), the temperature seasonality changes simulated by both iLOVECLIM and the GCMs reproduce the main latitudinal and continental gradients, as well as the influence of ice-sheet proximity on temperature seasonality changes." In line 750-754.

"Moreover, seasonality anomalies vary across GCMs, but they exhibit common spatial patterns that differ from those simulated by iLOVECLIM. To investigate the substantial differences between iLOVECLIM and the GCMs, we performed a series of sensitivity experiments with iLOVECLIM, in which key physical processes and model parameters were modified to assess their influence on the simulated LGM temperature seasonality" In line 759-763.

"Only by modifying the vertical radiative scheme used in iLOVECLIM were we able to substantially reduce the mismatch in seasonal anomalies between iLOVECLIM and the GCMs. This result suggests that the treatment of vertical radiative processes may

contribute to the distinctive LGM-PI temperature seasonality response simulated by iLOVECLIM." In line 769-773.

2. The main focus of the manuscript is the LGM–PI change in temperature seasonality. However, Fig. 5 mainly compares the inter-model spread in absolute LGM MTWA and MTCO. If the aim is to show that the disagreement in seasonality change is mainly associated with the winter response, it would be more direct to compare the inter-model spread in LGM–PI MTWA changes (ΔMTWA) and LGM–PI MTCO changes (ΔMTCO).

I suggest adding this comparison and, if the conclusion remains robust, using it to support the interpretation that MTCO is the main contributor to the inter-model differences in seasonality change.

In our manuscript, we examine the absolute climate states of MTWA and MTCO, rather than their changes between the LGM and PI, in order to disentangle the origin of the inter-model spread in temperature seasonality changes (LGM–PI) across Europe. While the models show good agreement in temperature seasonality under PI conditions (Fig. 5), our analysis of the inter-model spread focuses on identifying the respective contributions of MTWA and MTCO to the temperature seasonality at the LGM climate state. We find that the only substantial source of disagreement among the models is MTCO at the LGM. Moreover, models that simulate an increase in the amplitude of temperature seasonality at the LGM relative to the PI generally exhibit colder MTCO values at the LGM (e.g., CESM2-1).

We therefore retain the analysis of absolute ΔMTCO our objective is to identify the source of the inter-model spread, and because the models show good agreement in temperature seasonality under PI conditions, we therefore retain the analysis of absolute temperature states rather than temperature changes in Sec.3. ΔMTCO do not know if the disagreement is in part explained by disagreement for the PI. We nevertheless use the decomposition of temperature seasonality changes into MTWA and MTCO when investigating the individual processes driving these changes through our sensitivity experiments over Europe (Sec.4).

3. The PMIP simulations use different LGM ice-sheet reconstructions, while the largest disagreement in seasonality and MTCO occurs over and around the Fennoscandian Ice Sheet. The inter-model spread in this region may therefore reflect not only differences in model physics, but also differences in ice-sheet extent, elevation, and topographic representation.

Since the ensemble includes configurations of the same model using different ice-sheet reconstructions (e.g., iLOVECLIM), these may provide a useful opportunity to assess the sensitivity to ice-sheet boundary conditions. If a quantitative separation is difficult, it would still be helpful to acknowledge that both boundary conditions and model physics may contribute to the reported spread.

Thanks for this interesting point. Our study also provides an opportunity to assess, at least qualitatively, the relative influence of model formulation and ice-sheet boundary conditions. In particular, simulations using different configurations of the same model framework (iLOVECLIM and HadCM3) produce broadly similar spatial patterns of mean

temperature seasonality changes (LGM–PI) over the European ice-sheet regions, despite using different prescribed ice-sheet reconstructions (Fig.1). This result suggests that the boundary conditions of model may play an important role in shaping the simulated response, in addition to the prescribed ice-sheet boundary conditions.

However, while the changes in temperature seasonality are relatively little affected outside the FIS in the iLOVECLIM and HadCM3 simulations using two different ice-sheet reconstructions (GLAC-1D and ICE-6G_C), temperature seasonality is substantially modified over ice-covered areas, with differences of up to 5°C in the LGM-PI seasonality change (Fig.4). Interestingly, the use of these two ice-sheet reconstructions in the two model frameworks produces opposite effects on the changes in temperature seasonality over ice-covered areas (Fig.4), further indicating that the simulated response depends on the interaction between prescribed ice-sheet boundary conditions and model physics.

Moreover, the spatial extent of the temperature changes over these two areas depends on the prescribed ice-sheet masks (Figs.1 & 3), illustrating that ice-sheet boundary conditions do affect the spatial distribution of the simulated response. In particular, the presence of ice-covered areas tends to reduce the amplitude of LGM temperature seasonality relative to the PI, while differences in prescribed ice-sheet forcing, including albedo and elevation, have a more limited effect on the large-scale European temperature fields.

Although both ice-sheet boundary conditions and model physics may contribute to the inter-model spread, the iLOVECLIM configurations suggest that ice-sheet forcing primarily affects the spatial extent and distribution of temperature seasonality changes.
We have clarified this point in line 446-453 and emphasised that the sensitivity experiments in Section 4 investigate the processes underlying iLOVECLIM's distinctive response.

"Simulations with different prescribed ice-sheet reconstructions of the same model framework (iLOVECLIM and HadCM3) produce broadly similar spatial patterns of LGM-PI temperature seasonality changes (Fig. 1), suggesting that model formulation exerts an important influence on the simulated response. Although ice-sheet boundary conditions affect the spatial extent and local distribution of seasonality changes (Figs. 1, 3, and 4), the contrasting responses to different ice-sheet reconstructions across model frameworks indicate that model physics plays a substantial role in shaping the magnitude and spatial pattern of simulated temperature seasonality changes (Fig. 4)."

4. In Section 4, the authors conclude that differences in ice-sheet representation are unlikely to explain the iLOVECLIM–GCM seasonality mismatch, noting that even the extreme FlatIS experiment produces only a relatively moderate seasonality response. However, the Conclusion states that ice-sheet-forced albedo changes explain a large part of the simulated seasonality changes and may contribute to persistent inter-model discrepancies. These statements seem difficult to reconcile. The authors should clarify whether ice-sheet effects are considered important for the mean LGM–PI seasonality response, for the inter-model disagreement, or both, and revise the conclusions accordingly.

Figure R1 shows the annual changes in surface albedo over Europe resulting from the two sensitivity experiments associated with the FIS forcings (Flat and Dark), relative to the reference iLOVECLIM experiment. While removing the FIS topography does not substantially affect surface albedo compared with the reference iLOVECLIM simulation, the experiment without the ice-sheet mask still produces higher surface albedo values over the former FIS extent compared with PI conditions, although the area of enhanced albedo extends less far south than in the reference experiment. Despite the absence of initial snow cover, the annual cooling generated by the experiment leads to the development of persistent snow-covered areas.

This result is consistent with our sensitivity experiments but indicates that the sentence in the Conclusion - "Since we show that albedo changes from glacial forcings explain a large part of the simulated change in temperature seasonality, future research could focus on better quantifying land surface feedback, especially over ice-sheet regions." - was poorly formulated and could create confusion regarding the results presented in Section 4. We have therefore revised this sentence to clarify that the albedo changes associated with the glacial forcings contribute to the simulated changes in temperature seasonality, while the sensitivity experiments in Section 4 specifically investigate the processes responsible for these changes.

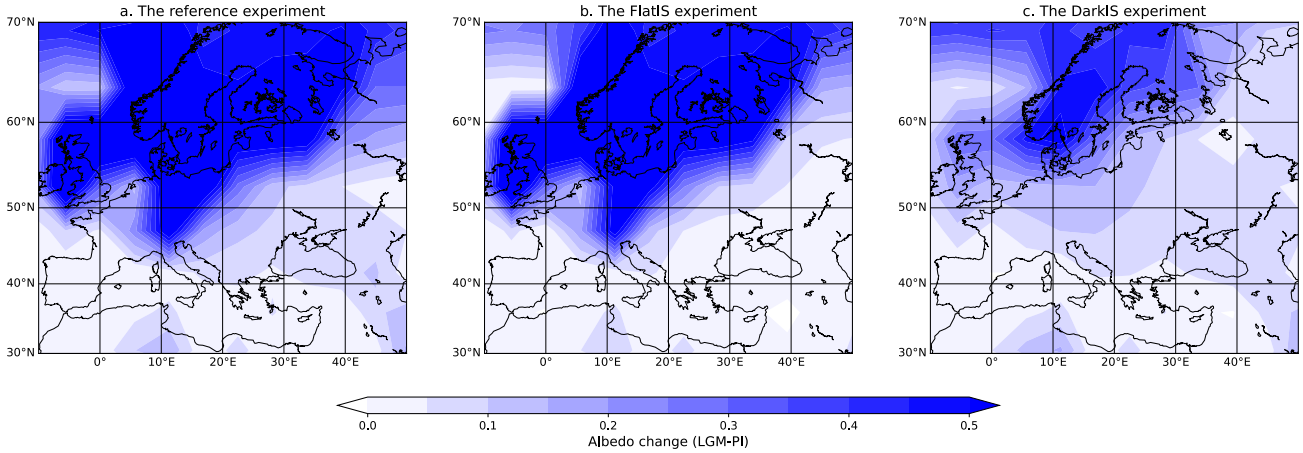


Figure R1. Annual albedo changes (LGM-PI) in the reference experiment (a) and in the sensitivity experiments: the flat (b) and dark (c) experiments. These results are derived from the model's native outputs and are not downscaled.

We therefore propose adding this figure as supplementary material to Section 4 to confirm and clarify the interpretation of this statement. We have clarified this point with the following sentence: "The MTCO is only weakly affected by albedo change ("DarkIS" experiment) because in winter seasonal fresh snow will be present anyways where the ice sheet is present. Only summer months, where seasonal snow melts away, present a darker albedo in "DarkIS" with respect to the reference simulation." In line 553-556.

5. The IRN experiment substantially reduces the difference between iLOVECLIM and the GCM multi-model mean, suggesting that the treatment of the vertical radiative profile may contribute to the distinctive iLOVECLIM winter response. However, a reduced model difference after modifying one process does not necessarily demonstrate that this process caused the

original discrepancy, as other mechanisms or compensating effects may also be involved. I would therefore recommend that the authors reconsider the causal framing in the Abstract, Discussion, and Conclusion to better reflect what can be supported by the current experiments.

Indeed, we have identified a model characteristic that reduces simulated winter temperature changes without significantly affecting summer temperatures, associated with the simplified treatment of the vertical radiative profile in the iLOVECLIM atmosphere, as described in Section 4.5. We therefore agree that the causal interpretation of the "IRN" experiment in relation to the inter-model spread in temperature seasonality changes should be nuanced. The iLOVECLIM sensitivity experiments are intended as a mechanistic exploration of the processes underlying its distinctive response, rather than as a demonstration of the causes of the inter-model spread across the GCMs.

For instance, in the Conclusion, we propose replacing "Only by modifying the vertical radiative scheme used in iLOVECLIM were we able to reduce this mismatch in seasonal anomalies between iLOVECLIM and the GCMs. This suggests that the absence of an explicit vertical radiative representation of iLOVECLIM contributes to making this model different from the other ones in terms of LGM-PI temperature seasonality changes." with "Only by modifying the vertical radiative scheme used in iLOVECLIM were we able to substantially reduce the mismatch in seasonal anomalies between iLOVECLIM and the GCMs. This result suggests that the treatment of vertical radiative processes may contribute to the distinctive LGM–PI temperature seasonality response simulated by iLOVECLIM." We have applied the same nuance to the corresponding statements in the Abstract and Discussion of the revised manuscript.

6. The authors note that CESM2-1 behaves as an outlier in terms of magnitude but retain it in the ensemble analysis. While this is reasonable, I wonder to what extent this outlier influences the inter-model standard deviation in Fig. 5, particularly the large MTCO spread. It would be helpful to clarify the robustness of this result.

Although CESM2-1 behaves as an outlier in terms of LGM–PI temperature seasonality changes compared with the other GCMs over Europe, the inter-model standard deviation (STD) of MTCO changes, which largely drives the differences in temperature seasonality changes, is not significantly affected (< 1°C) by excluding CESM2-1 from the model ensemble considered in this study. The differences in STD between the two ensembles, with and without CESM2-1, are negligible, as shown in Figure R2a-b.

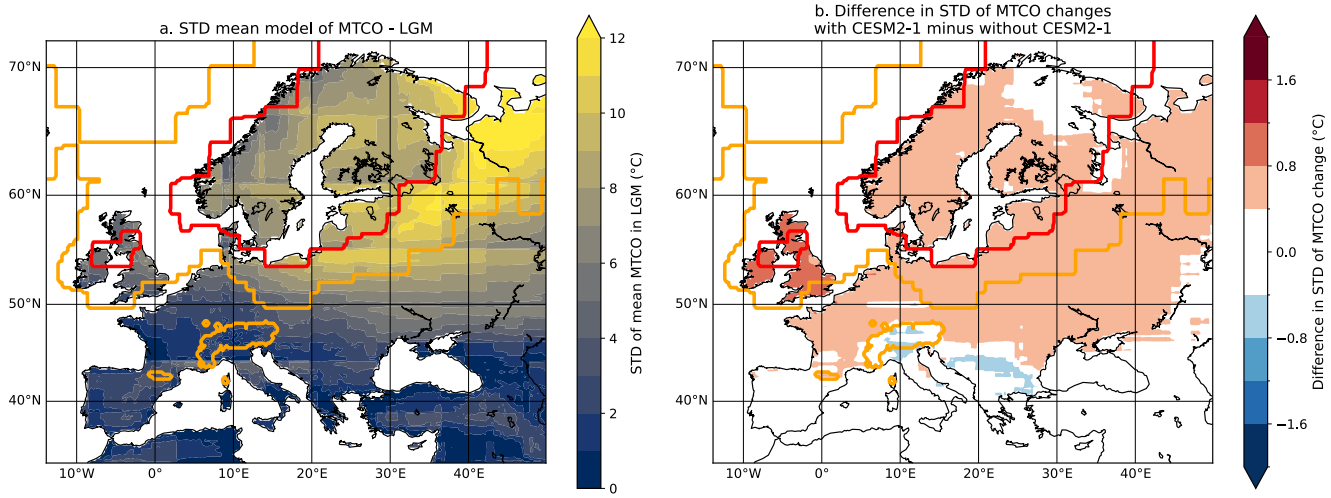


Figure R2. Difference in the standard deviation (STD) of MTCO changes between the two model ensembles, with (a) and without CESM2-1 (b), in the dataset considered in this study. Red and orange contour lines indicate the common and maximum ice sheet extents, respectively, among all models, including GCMs and iLOVECLIM.

This result suggests that the inter-model spread reported in this manuscript is robust to the strong sensitivity of CESM2-1, owing in part to the relatively large number of GCMs included in our dataset (19 models).

7. The GCM outputs are remapped to 0.25° using nearest-neighbor interpolation, whereas iLOVECLIM is dynamically downscaled to 0.25°. These procedures are fundamentally different, as remapping does not add new spatial information. I suggest distinguishing them more clearly throughout the manuscript and clarifying whether this difference could affect the comparison, particularly around the FIS where topography is important.

We agree that nearest-neighbour remapping of the GCM outputs and online downscaling of iLOVECLIM are fundamentally different procedures and have clarified this distinction throughout the revised manuscript. The GCM outputs are remapped to the common 0.25° grid using nearest-neighbour interpolation, which does not add spatial information, whereas our iLOVECLIM version is dynamically downscaled to 0.25° using a regional atmospheric model that accounts for interactions between global-scale and regional-scale processes. Firstly, interpolating the GCM outputs onto our downscaling grid provides a common spatial grid for point-to-point comparison of climate outputs and evaluation of climatic biases.

By comparing three iLOVECLIM configurations, our dynamically downscaled simulations show lower temperature seasonality changes north of the FIS than the iLOVECLIM ICE-6G_C configuration, despite using similar ice-sheet reconstructions (−12°C vs. −9°C on average; Fig. 4). Compared with nearest-neighbour interpolation, online downscaling may modify surface temperatures over high-elevation regions by explicitly representing fine-scale topographic effects. This can lead to lower annual mean temperatures in high-mountain regions and potentially reduce the amplitude of seasonal temperature variations. In addition, the online downscaling process affects the local calculation of

saturation vapour pressure, which decreases with temperature. This effect can substantially increase precipitation at high elevations compared with the non-downscaled products. Overall, the main advantage of the dynamical downscaling is to provide finer spatial information by resolving regional-scale variations in surface climate, particularly over areas of complex topography.

We then use nearest-neighbour interpolation to compare the native fields of the GCMs and iLOVECLIM on a common grid, thereby minimizing methodological biases in the analysis. Moreover, our analysis focuses primarily on large-scale spatial patterns and spatially averaged changes in temperature seasonality, for which we consider the common-grid comparison to remain informative.

We have clarified this limitation in the revised manuscript, in section 3.1.

"To capture equilibrium climate states and mean temperature seasonality cycles, we analyze 50 years of monthly surface air temperature (tas) outputs interpolated on a common 0.25°×0.25° grid covering Europe (35°N-70°N and 10°W-50°E) using a nearest neighbour interpolation. This interpolation procedure ensures that the native fields of the GCMs and iLOVECLIM are compared on a common grid." In line 147-150.

8. The integration lengths and equilibration status of the sensitivity experiments are not sufficiently clear. This is particularly relevant for FWF and BRINES, given the longer adjustment timescales of the ocean circulation. It would be helpful to clarify the integration and averaging periods and whether these experiments had reached a sufficiently equilibrated state.

We agree with the reviewer to clarify climate equilibrium state of our runs. All sensitivity experiments were initialized from a restart of the 5,000-year reference iLOVECLIM simulation. The last 50 years of each simulation were retained for the analysis in order to capture the equilibrium state and minimize the influence of transient adjustment. This long integration period is particularly relevant for the FWF and BRINES experiments, given the longer adjustment timescales of the ocean circulation. For each sensitivity experiment, only the parameter specifically modified in that experiment was selected for comparison with the corresponding results from the reference simulation. These comparisons are presented in Figures 1-4. *We have clarified the integration length and averaging period in line 251-252 of the revised manuscript.*

Minor comments:

1. PMIP simulations are averaged over 50 years whereas iLOVECLIM is averaged over 100 years. Please explain the reason for this difference and also check the Fig. 4 caption, which states that the last 50 years are used for each model.

In this study, temperature seasonality changes from both the GCMs and iLOVECLIM are estimated from the LGM equilibrium climate state over the last 50 years of the simulations. Therefore, the same averaging period is used for all models. *In the original manuscript, the*

statement "the last 100 yr" (line 237) was incorrect and has been replaced by "the last 50 yr" in the revised manuscript.

2. Please clarify whether spatial averages are area weighted, as unweighted averaging would overrepresent high-latitude grid cells.

Spatial means of climate variables over the ice-free surfaces of Europe are calculated using the grid-cell areas provided by each model, in order to account for differences in grid-cell size, particularly the larger grid cells at higher latitudes. To do so, we used the variable "areacell" provided in the NetCDF files listed in the "Data availability" section of the present manuscript. ***We have added this information in lines 374-375:***
"Fig.2a shows the annual temperature cycle, spatially averaged over the continents, with grid-cell-area weighting, simulated for the LGM by each model."

In lines 391-392: "These spatial means are area-weighted and include all continental grid cells, both ice-covered and ice-free."

And the Figure 4 caption of the revised manuscript.

3. For the FWF experiment, please specify the exact spatial region over which the 0.2 Sv freshwater forcing is applied, its duration, and the resulting AMOC state.

We thank the reviewer for pointing this out. In the FWF experiment, a freshwater forcing of 0.2 Sv is applied over the two geographical areas which correspond to:

- **Hudson River outlet (HRO)**
- **MacKenzie River Outlet (MRO)**

Following the experimental setup of *Roche et al. (2010)*, which provides an initial AMOC strength of approximately 30 Sv under LGM conditions.

This freshwater forcing is applied throughout the experiment. In the 0.2 Sv experiments, the freshwater forcing is sufficient to induce a temporary and substantial weakening of the AMOC, partially approaching an "off" state in the model (*Roche et al., 2010)*. ***We have clarified these details in the revised manuscript, in the line 276-279.***

"In one experiment, we impose a large freshwater flux of 0.2 Sv (1 Sv = 10^6 m^3 s^{-1}) over the Hudson and Mackenzie River outlets, leading to an "off" state of the AMOC. Under LGM conditions, the initial AMOC strength is approximately 30 Sv (Roche et al., 2010)."

Refs.

Roche, D.M., Wiersma, A.P. & Renssen, H. A systematic study of the impact of freshwater pulses with respect to different geographical locations. Clim Dyn 34, 997–1013. https://doi.org/10.1007/s00382-009-0578-8, 2010.

4. In the Fig. 3 caption, "35°N–30°N" appears to be a typo, as the Methods describe the study region as 35–70°N. Please check.

In agreement with the results of the two spatial profiles shown in Figure 3, the range indicated in the caption was incorrect. ***We have therefore replaced "35°N–30°N" with "35°N–70°N" in the Figure 3 caption of the revised manuscript.***

5. Expressions such as "MTCO decreases by +5 to +15°C" contain an apparent inconsistency between the sign and the wording. Please revise throughout.

We agree that this wording could be confusing. We have clarified that the MTCO changes reported for the "IRN" experiment (Section 4.5) are expressed relative to our reference iLOVECLIM simulation. ***This clarification has been added in lines 621-622 of the revised manuscript, and the expressions have been revised accordingly throughout the manuscript.***

6. Please standardise terminology and spelling throughout, including "Fennoscandien/Fennoscandian," iLOVECLIM, experiment names, and "Mean Model/multi-model mean."

We have conducted a thorough and systematic proofreading of the entire revised manuscript to identify and correct inconsistencies in terminology, spelling, abbreviations, and the naming of experiments. Particular attention was paid to ensuring consistent use of terminology throughout the main text, figures, figure captions, tables, and Methods section. We have also carefully checked the consistency of model names, experiment names, geographical terms (e.g., "Fennoscandian"), and expressions such as "Mean Model" and "multi-model mean." In addition, the spelling and formatting of iLOVECLIM have been standardized throughout the manuscript. These revisions were made to ensure overall coherence and consistency between the different sections and graphical elements of the manuscript.

7. Some information in Table 1 should be checked carefully. For example, "ICE-6C_C" for MPI-ESM1-2 may be a typo for "ICE-6G_C." The PMIP/CMIP designation for HadCM3 should also be verified.

We have carefully checked and revised the information provided in Table 1. Several typographical errors and inconsistencies in abbreviations have been corrected, and the prescribed ice-sheet configurations have been systematically verified for all models. We have also checked the PMIP/CMIP designations and the corresponding model and ice-sheet configurations to ensure consistency with the simulations used in this study. ***Given these corrections and updates, we have replaced Table 1 with a revised version in the manuscript.***

8. Please standardise "near-neighbour" to "nearest neighbour" in the Methods.

We have standardised the terminology used to describe spatial interpolation throughout the revised manuscript and replaced "near-neighbour" with "nearest neighbour" where appropriate.

9. L59, iLOVECLM

The abbreviation has been corrected to "iLOVECLIM".

10. L225, peloclimate

The typo has been corrected to "paleoclimate".

11. L921, Citation year for Harmand et al.: it is cited as 2025 in the text but listed as 2015 in the references.

The citation should refer to Hernandez et al. rather than Harmand et al.
The publication year has been corrected and is now consistent between the citation in the main text and the reference list of Hernandez et al.