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 #2: RC2: 'Comment on egusphere-2026-3988', Anonymous Referee #2, 17 Sept. 2026

Temperature seasonality is important for interpreting proxy-based temperature reconstructions and evaluating climate-model performance. In this study, the authors compare simulations from PMIP3-CMIP5 and PMIP4-CMIP6 models with dynamically downscaled iLOVECLIM simulations to investigate changes in European temperature seasonality between the Last Glacial Maximum and the pre-industrial period. The results indicate a general decrease in temperature seasonality over southern Europe and an increase over northern and eastern Europe, although substantial inter-model differences occur near the Fennoscandian ice sheet. By separating the mean temperatures of the warmest and coldest months, the authors identify winter temperature as the principal source of both seasonality changes and inter-model spread. A series of iLOVECLIM sensitivity experiments further suggests that modifying the prescribed vertical radiative profile reduces the mismatch between iLOVECLIM and the GCM ensemble. However, two key issues require further clarification:

The Abstract and Conclusions lack quantitative precision. Although the simulations and sensitivity experiments provide highly quantitative results, the main findings are described largely with qualitative terms such as "slight," "large," "stark," and "substantial." Please report representative magnitudes and spatial ranges of the seasonality changes, differences between the GCMs and iLOVECLIM, the contribution of MTCO, and the extent to which the sensitivity experiment reduces the iLOVECLIM–GCM mismatch. This would make the conclusions more precise and enable readers to assess the robustness and climatic significance of the results.

We totally agree that quantitative information should be reported in these two sections in the next revision of the manuscript.

These corrections include: "with standard deviations of up to 12°C" and "Models simulate a slight and relatively consistent increase in temperature seasonality changes along the Atlantic coast, ranging globally from −3°C to +10°C, but a larger and more variable increase over eastern Europe, ranging from −5°C to +20°C." in the abstract, and "We show that, despite a substantial inter-model spread (STD of up to 12°C)," in the conclusion.

The physical interpretation of the winter-temperature differences remains incomplete. The manuscript attributes the anomalous winter temperatures in iLOVECLIM mainly to its prescribed vertical radiative profiles and simplified vertical atmospheric representation. This explanation is plausible and broadly consistent with current understanding, but the underlying mechanism could be discussed further. Modern European winter surface temperatures are strongly affected by stratosphere–troposphere coupling through the polar vortex, planetary-wave propagation, tropospheric jet, and associated circulation changes. The sensitivity experiment demonstrates the importance of atmospheric vertical structure, but does not by itself establish radiative parameterization as the direct cause of the MTCO bias. The authors should discuss, with reference to relevant literature, whether differences in stratosphere–troposphere coupling could contribute to the contrasting winter responses among models. If the simplified atmospheric structure of iLOVECLIM precludes such analysis, this limitation and its implications for attributing the MTCO bias should be stated explicitly.

Related to General Comment 2, the sensitivity experiments suggest that the simplified vertical atmospheric structure may contribute to the underestimated temperature seasonality. Could the relevant vertical structures and circulation characteristics be compared directly between iLOVECLIM and the GCMs?

Although we identified a significant contribution from the lack of explicit atmospheric representation in iLOVECLIM to winter climates over Europe, particularly near the FIS region (Figs. 6g & 7a–b), we agree that the submitted manuscript would benefit from investigating contrasts in atmospheric circulation patterns between the experiments. As an intermediate-complexity model, iLOVECLIM uses prescribed regional profiles of temperature, humidity, and ozone, including a Greenland profile, to calculate shortwave radiative fluxes through 3 atmospheric layers (200, 500 et 800 hPa, Opsteegh et al., 1997) rather than simulating evolving atmospheric structure as GCMs do.

Over the Greenland Ice Sheet, particularly in winter, the snow- and ice-covered surface favours strong radiative cooling near the surface and the development of stable near-surface temperature inversions (Hoch et al., 2007). In Europe, by contrast, the vertical atmospheric structure is much more heterogeneous and depends on latitude, topography, snow cover, and, importantly, exchanges with the North Atlantic and synoptic-scale circulation. Heat and moisture advection can substantially modify temperature and humidity profiles and the depth of the atmospheric layer influenced by surface processes. Therefore, applying a Greenland-derived vertical profile only over the LGM Eurasian ice sheet may not fully represent the atmospheric conditions prevailing over Europe.

Given the winter atmospheric feature in iLOVECLIM and the pronounced inter-model spread in seasonal temperature changes, we analyse and decompose planetary-scale geopotential-height changes (LGM-PI) in the lower and high troposphere to investigate differences in large-scale atmospheric circulation. Geopotential-height anomalies provide a useful diagnostic of anomalous troughs and ridges and their potential influence on surface climate through atmospheric heat transport (e.g., Beghin et al., 2016).

The 500 hPa level is particularly relevant for characterizing the mid-tropospheric circulation and thermal advection processes, which are closely related to surface temperature patterns and strongly influenced by glacial ice-sheet boundary conditions (e.g., Justino et al., 2005). However, the 800 hPa level available in iLOVECLIM has no direct equivalent in the GCM simulations, for which 850 hPa is the closest available level, thereby limiting inter-model comparisons at this altitude. The 200 hPa level, located in the upper troposphere near the tropopause (approximately 12 km), provides complementary insights into the atmospheric circulation. In particular, analysing planetary waves at this level helps characterize the large-scale circulation patterns in the upper troposphere and assess the dynamical response of the atmosphere to glacial cooling, including potential changes in the structure and propagation of planetary waves and their relationship with the upper-level westerly flow and jet streams.

Comparing LGM-PI changes in lower-tropospheric geopotential patterns across models therefore allows us to assess whether the inter-model spread in surface-temperature response is associated with distinct changes in large-scale atmospheric circulation. This provides a dynamical perspective complementary to the analysis of radiative processes and helps identify the mechanisms contributing to the divergent climate responses simulated by the models.

To further investigate the relationship between atmospheric circulation and seasonal temperature changes, we analyse winter and summer geopotential-height anomalies during the LGM and PI periods, expressed as deviations from the corresponding zonal-mean geopotential heights over Europe and the North Atlantic Ocean (Figure R3).

Due to modified climate forcings in iLOVECLIM experiments, atmospheric circulations are significantly affected under LGM conditions, especially during winter (Fig.R3). These modifications in atmospheric circulation patterns are comparable to GCMs mean model (Fig.R3h). While only the IRN experiment produce temperature seasonality changes more similar than the GCMs, compared to other iLOVECLIM experiments, we demonstrate that atmospheric circulation changes are not the only one process to explain the seasonality disagreement between iLOVECLIM and the GCMs.

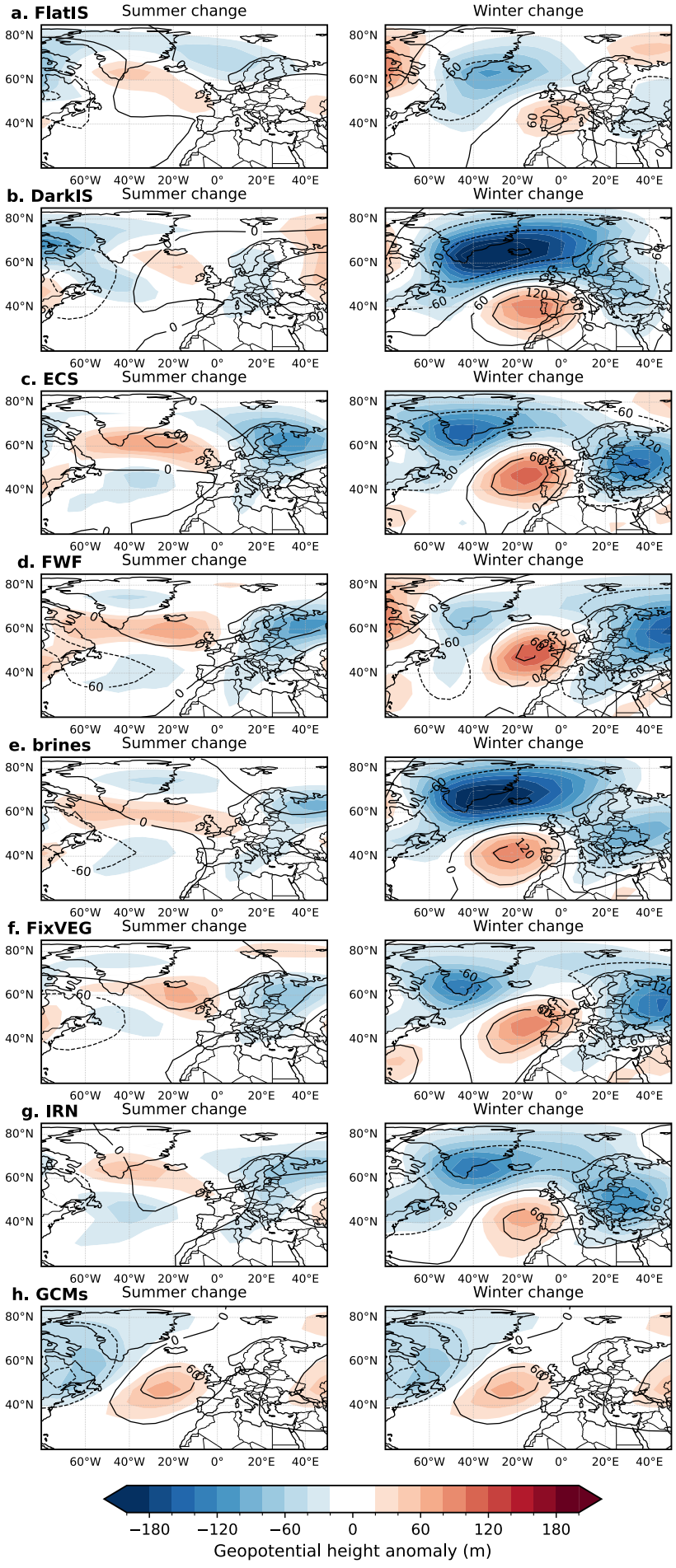

a. FlatIS
Summer change
Winter change
b. DarkIS
Summer change
Winter change
c. ECS
Summer change
Winter change
d. FWF
Summer change
Winter change
e. brines
Summer change
Winter change
f. FixVEG
Summer change
Winter change
g. IRN
Summer change
Winter change
h. GCMs
Summer change
Winter change
80°N
60°N
40°N
60°W 40°W 20°W 0° 20°E 40°E
−180 −120 −60 0 60 120 180
Geopotential height anomaly (m)

Figure R3. Maps of geopotential height changes (LGM–PI; in m, with the zonal mean subtracted) during summer (first column) and winter (second column) at 500 hPa (shading) and 200 hPa (black contours). While each row corresponds to an iLOVECLIM experiment, the last row ("GCMs") shows the monthly geopotential height changes averaged across the GCMs. The contour interval is 60 m, with negative contours dashed. Positive and negative anomalies correspond to anomalous anticyclonic and cyclonic circulation, respectively.

We have therefore revised the discussion to investigate the potential contribution of atmospheric dynamical processes. We propose to discuss this point in Section 4, with additional supporting analysis provided in the Supplementary Materials of the future revised manuscript: "Since atmospheric circulation is a major driver of European seasonality (e.g., Wang et al., 2011; Simpson et al., 2023), we investigated circulation changes between the LGM and PI by tracking changes in geopotential height above the Northern Atlantic Ocean in the different sensitivity experiments (Fig. S9). All tests show changes in atmospheric circulation, particularly during winter. Although the IRN experiment is the only one to reduce the mismatch between iLOVECLIM and GCM temperature seasonality changes over the last deglaciation (Fig. 7), the associated atmospheric circulation changes are not markedly different from those in the other sensitivity experiments. This suggests that changes in atmospheric circulation alone cannot explain the observed discrepancy in LGM seasonality between iLOVECLIM and GCMs." In line 641-650.

Specific Comments:

Could the authors compare the similarities and differences between the PMIP3–CMIP5 and PMIP4–CMIP6 results? This comparison could be supported by previous studies assessing changes across PMIP/CMIP generations.

We acknowledge that this analysis was missing from our manuscript. Although LGM cooling is similar among the models (Fig.S3), the spatially averaged changes in temperature seasonality are not significantly different between the PMIP3 and PMIP4 generations (Fig.4). These averages also show no clear distinction between ice-covered and ice-free areas, in contrast to the iLOVECLIM results.

Please define or indicate the boundary between northern and southern Europe, as the division varies among geographical and climatic classification schemes.

We have clarified the geographical boundaries of the regions considered by specifying the latitude ranges used to define the different areas of Europe.
Done

Because the analysis includes only two time slices, it is not accurate to describe the results as the full evolution "since the LGM." Terms such as "changes between the LGM and pre-industrial period" would be more precise, including in the title.

Thanks for your remark.

We changed the title accordingly: « European seasonal temperature change between the Last Glacial Maximum and the pre-industrial period from climate models » and also throughout the text.

Please discuss the physical mechanisms underlying the meridional and zonal patterns shown in Fig. 3, rather than describing the spatial changes alone.

We thank the reviewer for this comment. We agree that the geographical gradients should be discussed in relation to the physical mechanisms. However, the two geographical gradients alone do not allow us to directly identify or quantify the underlying physical processes. In Section 3.1, we therefore relate the observed regional patterns to the proximity to the ocean and to the ice sheets across Europe. In particular, the large inter-model spread in LGM-PI temperature seasonality changes at high latitudes (> 65°N; from −12°C to +30°C) may partly reflect differences in the extent of the prescribed ice-sheet reconstructions (Fig. 3a), as temperature seasonality is strongly affected by the nature of the underlying surface, whether ice-covered or ice-free (Fig. 4). In contrast, the simulations along the Atlantic coast show a more consistent response, with values ranging from −3°C to +10°C (Fig. 3b), except for the highly sensitive CESM2-1 simulation, which reaches a seasonality change of +30°C. Differences in climate sensitivity may also contribute to the weaker LGM cooling and consequently to larger changes in temperature seasonality in this simulation.

The iLOVECLIM sensitivity experiments presented in Section 4 provide a complementary process-based approach, allowing us to isolate individual mechanisms and quantify their effects on surface temperatures and temperature seasonality.
We have therefore revised Section 3.1 (relative to Fig.3) to better discuss the geographical patterns in terms of these physical controls, while reserving the more detailed process-based interpretation for Section 4.

Minor comments:

Line 1: Consider replacing "since the Last Glacial Maximum" with "between the Last Glacial Maximum and the pre-industrial period," because only two time slices are compared.

Indeed, we only consider the LGM and PI equilibrium climate states.
Done

Figure 5: Please explain what the red line represents. The meaning of "common ice-sheet extent" is also unclear and should be defined explicitly in the caption.

This should be made more explicit by changing "common" to "minimum".
We have described this contour in the figure caption: "While the orange contour line represents the maximum ice-sheet extent, the red line marks the boundary of the region considered to be glaciated in all models."