Response File – Climate of the Past Manuscript cp-2026-590

DOI: https://doi.org/10.5194/egusphere-2026-1590
Title: Advancing Last Glacial Maximum paleoclimate reconstructions in Europe using pollen data: a multi-method (mega)biomization approach

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-2026-1590', Anonymous Referee #2, 10 May 2026

Overview and general recommendation:
This study presents a methodologically innovative and well-organized contribution to Last Glacial Maximum (LGM) paleoclimate reconstruction in Europe. By integrating three complementary pollen-based methods (MAT, WA-PLS, and CREST) and introducing a novel (mega)biome affinity-score weighted average approach, the authors effectively mitigate threshold effects and non-linear biases inherent in traditional single-biome dominance methods, thereby enhancing the robustness and spatial detail of temperature reconstructions. The paper is logically structured, with clear articulation of methods, comprehensive data handling, and rigorous cross-validation; figures and tables effectively illustrate inter-method consistency and regional anomalies. The open data and code further support reproducibility. Overall, this work provides valuable benchmarks for model–data comparisons and offers a transferable framework for improving paleoclimate reconstructions under non-analogue conditions.

We thank the reviewer for their positive and enthusiastic comments regarding our work.

I recommend the paper for publication, but I have the following comments:

1. *The quality of modern pollen data is more important than the methods themselves for climate reconstruction. I hope the authors can present the analogue quality for each pollen record and the locations of the best analogues for LGM fossil pollen spectra. I think the best analogues should be restricted to high altitudes and latitudes, but we need to know their locations and how many sites are involved.*

We agree that the quality and representativeness of the modern calibration dataset are critical aspects of pollen-based climate reconstruction, particularly for calibration datasets covering large spatial scales and climatic periods that differ drastically from present-day conditions. In this context, identifying the geographical distribution and ecological affinity of the best modern analogues may provide useful and powerful information regarding the structure of the calibration space and the implications for potential no-analogue situations during the LGM.

In contrast, in this study, our methodological approach does not rely on the direct selection of best analogues from the calibration dataset for reconstructing LGM climate conditions. Instead, it is based on a different framework in which we apply a (mega)biomisation-based preconditioning

step aimed at constraining analogue selection within a global calibration space. This step structures the analogue search according to ecological affinities between modern and fossil pollen assemblages, rather than relying solely on statistical similarity within the calibration dataset. In addition, we apply a weighting of reconstructed climatic variables based on (mega)biome-derived scores.

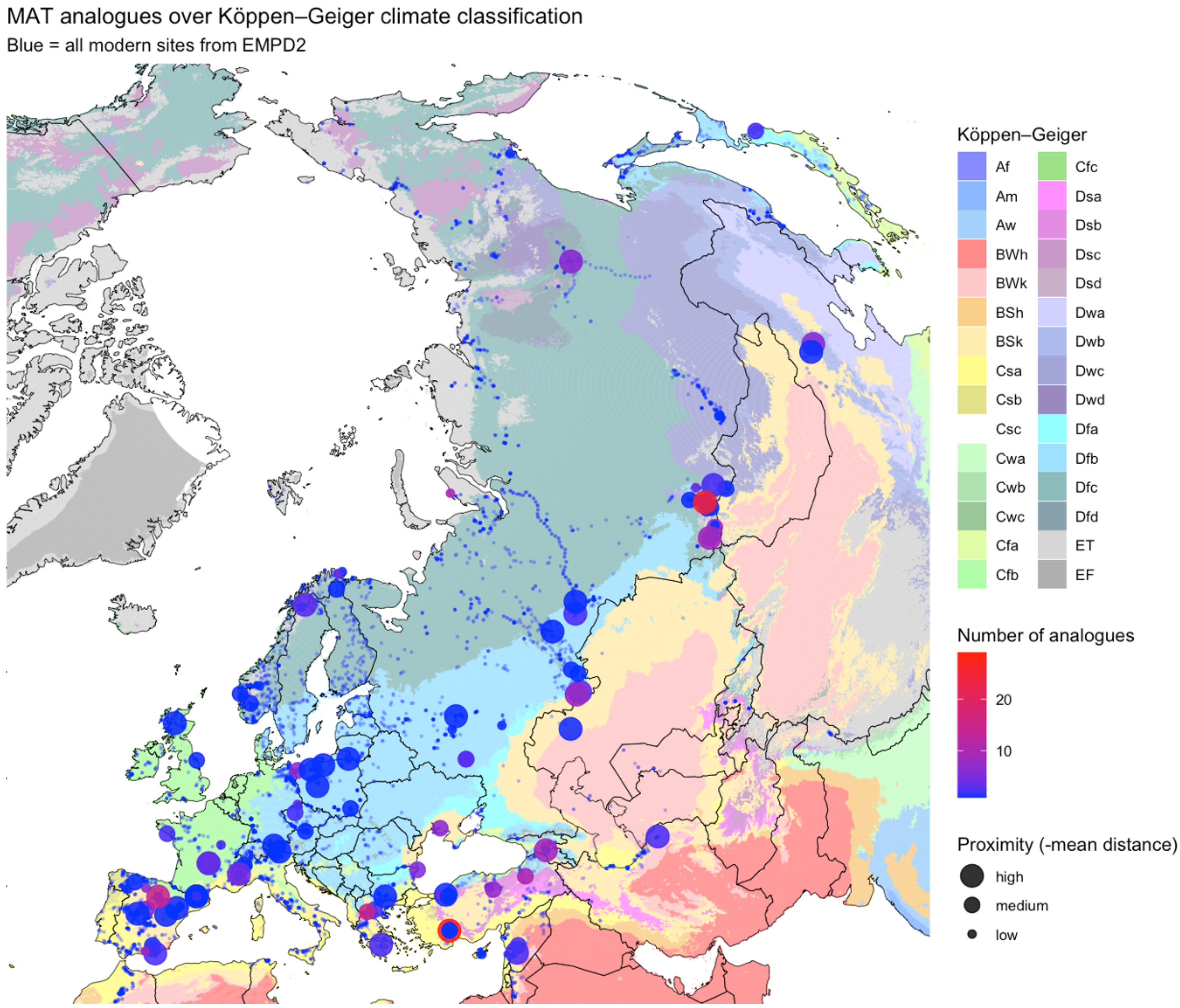
Within this framework, analyses based on identifying best analogues using the full EMPD2 calibration dataset (global calibration, i.e., without biomisation preconditioning) should not be interpreted as an independent validation of the climate reconstructions. Rather, they are used as a diagnostic tool/exercise, reflecting, at least in part, differences between approaches in their ability to sample the full range of the reference climatic space in a representative way, including cold conditions, particularly regarding how the reference climatic space is sampled.

Here, we provide a map of the selected best analogues derived from each fossil pollen data, using MAT method (Fig.R2), in order to clarify this point and to avoid any potential misinterpretation. This map reports the occurrences of the k best analogues across fossil sequences (Table 1). The k values, close to 10, are chosen to minimize reconstruction errors (RMSE) relative to observed climates. Note that the abundances of LGM samples vary between sites - The 42 fossil localities therefore contribute unevenly to the frequency distribution of modern assemblages.

Figure R2 shows modern samples identified as analogues of LGM pollen assemblages :

i. **in Western Siberia, where assemblages are relatively sparse in EMPD2, forming a heterogeneous sampling network mainly associated with cold, no dry-season Köppen–Geiger climates (Dfb & Dfc);**
ii. **in Scandinavian regions corresponding to the extent of the Fennoscandian ice sheet, also assigned to similar Köppen–Geiger climate types; however, the best analogues from this region exhibit, on average, lower dissimilarity values;**
iii. **in southern Europe (<40°N), particularly around the Mediterranean basin, under hot dry (Csa) to arid desert (BWh) conditions. Some modern samples are repeatedly selected across LGM pollen iterations. This region includes Spain, which has the densest modern pollen coverage.**

Although 12 of the 43 fossil sequences originate from Italy, no modern vegetation analogues corresponding to these LGM assemblages are currently found in this region.



Af = Tropical, rainforest	Cwc = Temperate, dry winter, cold summer
Am = Tropical, monsoon	Dsa = Cold, dry summer, hot summer
Aw = Tropical, savannah	Dsb = Cold, dry summer, warm summer
BSk = Arid, steppe, cold	Dsc = Cold, dry summer, cold summer
BSh = Arid, steppe, hot	Dwa = Cold, dry winter, hot summer
BWk = Arid, desert, cold	Dwb = Cold, dry winter, warm summer
BWh = Arid, desert, hot	Dwc = Cold, dry winter, cold summer
Csa = Temperate, dry summer, hot summer	Dwb = Cold, dry winter, warm summer
Csb = Temperate, dry summer, warm summer	Dfa = Cold, no dry season, hot summer
Csc = Temperate, dry summer, cold summer	Dfb = Cold, no dry season, warm summer
Cfa = Temperate, dry summer, hot summer	Dfc = Cold, no dry season, cold summer
Cfb = Temperate, dry summer, warm summer	Dfd = Cold, dry winter, very cold winter
Cfc = Temperate, no dry season, cold summer	EF = Polar, frost
Cwa = Temperate, dry winter, hot summer	ET = Polar, tundra
Cwb = Temperate, dry winter, warm summer	-

Figure R2. Map showing the best modern analogues of LGM pollen assemblages in Europe, along with Köppen-Geiger climate classifications (*Beck et al., 2018*). Blue points represent all modern sites included in the EMPD2 pollen dataset, whereas blue and red larger points highlight the selected best analogues identified using the MAT method. The size of the red markers is inversely proportional to the dissimilarity values, meaning that larger points correspond to better analogues. The point sizes should therefore be interpreted comparatively. The definitions of Köppen-Geiger climate classes are provided in the table associated with this figure.

Without any preprocessing constraint (i.e., biomisation), the MAT samples more than 50% of its analogues from temperate climates (Csa), despite these being approximately twice as rare in the dataset. Sampling across the remaining Köppen–Geiger classes containing the best analogues is broadly homogeneous (Fig R3). In contrast, arid climate classes are strongly under-represented or entirely absent among selected analogues (e.g., BSk and BWh). These patterns, derived from a global calibration framework and analysed at the sample level, are not aggregated to represent LGM best analogues at the site scale.

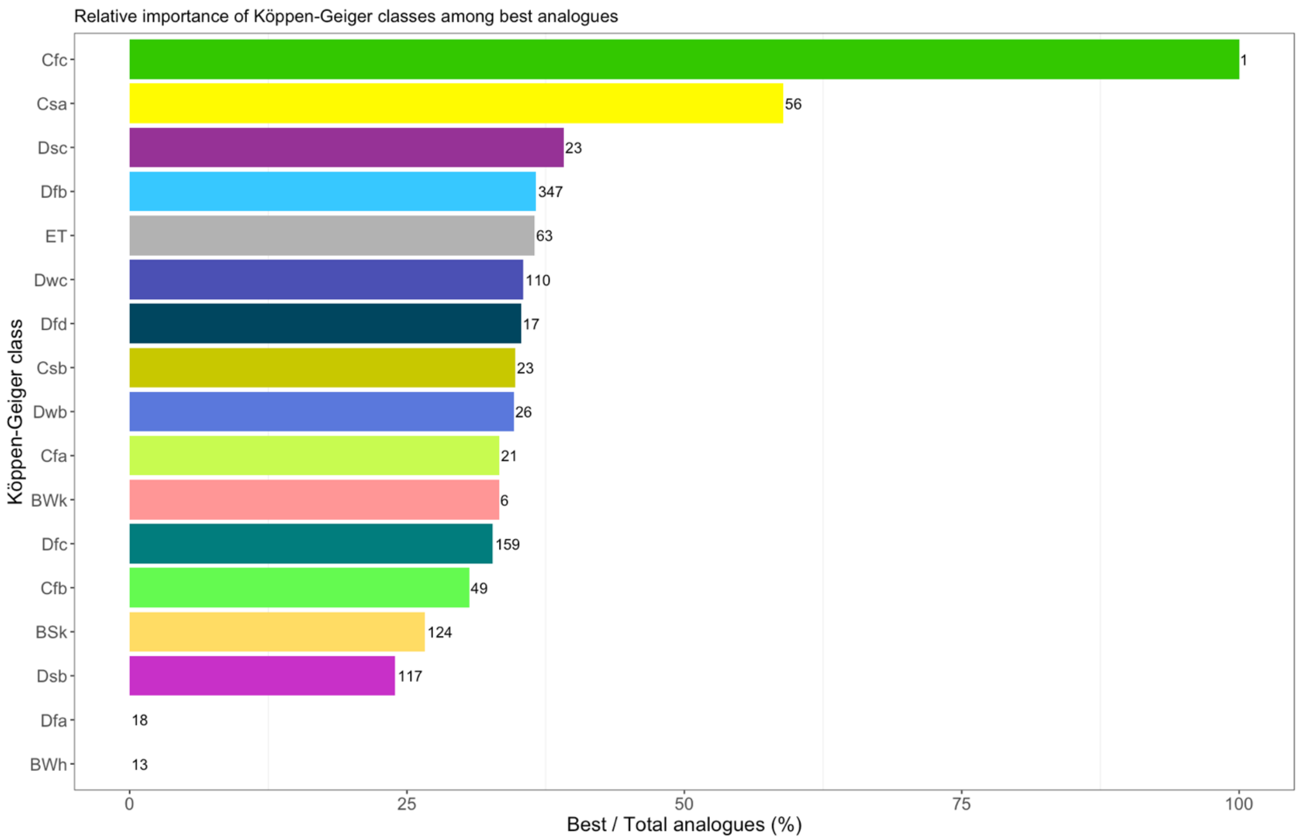


Figure R3. Histogram showing the relative fractions (%) of modern analogue samples selected by Köppen–Geiger climate class. The labelled values indicate the number of best modern samples selected for each class.

To better link fossil pollen assemblages to their best modern analogues, we aggregate analogue-climate class results at the fossil site level and assign modern biome classifications to the selected analogues. When these analogues are grouped by site (Fig R4), cold Köppen-Geiger climates with no dry season (Dfd and Dfc) dominate the modern analogue assemblages, closely matching the cold steppe conditions (COST) inferred from our biomisation procedure (Fig R5). We also observe that sites reconstructed from a wider diversity of Köppen–Geiger climate classes generally correspond to a greater diversity of LGM biome assignments.

As also suggested in Fig 10 of the manuscript, these results indicate that the MAT method remains effective, even under a global calibration framework, in selecting modern analogues consistent with cold climatic conditions inferred from LGM pollen data. In summary, the distribution of analogues across Köppen-Geiger climate classes and biome categories highlights the complexity of analogue selection, which is not solely driven by latitude but primarily reflects broader European climatic gradients.

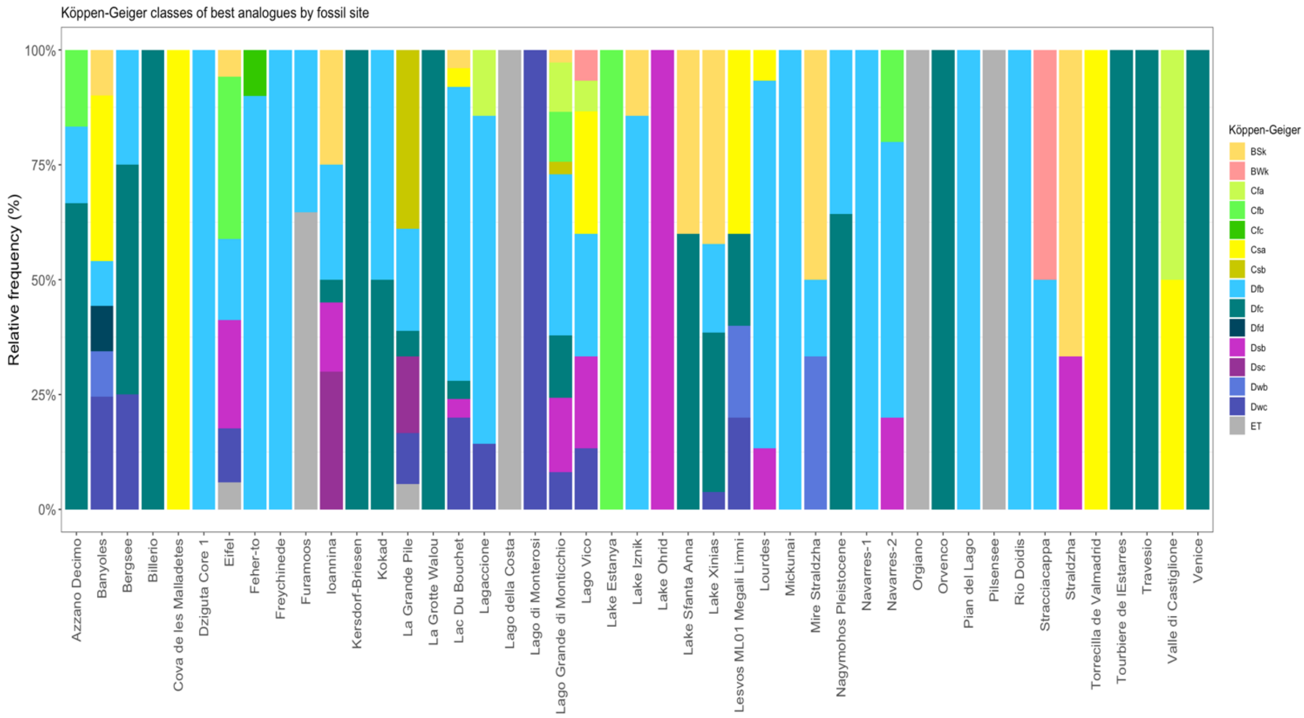


Figure R4. Cumulative histogram showing the distribution of best selected analogues assigned to Köppen-Geiger climate classes (*Beck et al., 2018*), averaged by site. These analogues are obtained by comparison with LGM pollen assemblages (Table 1 of the manuscript).

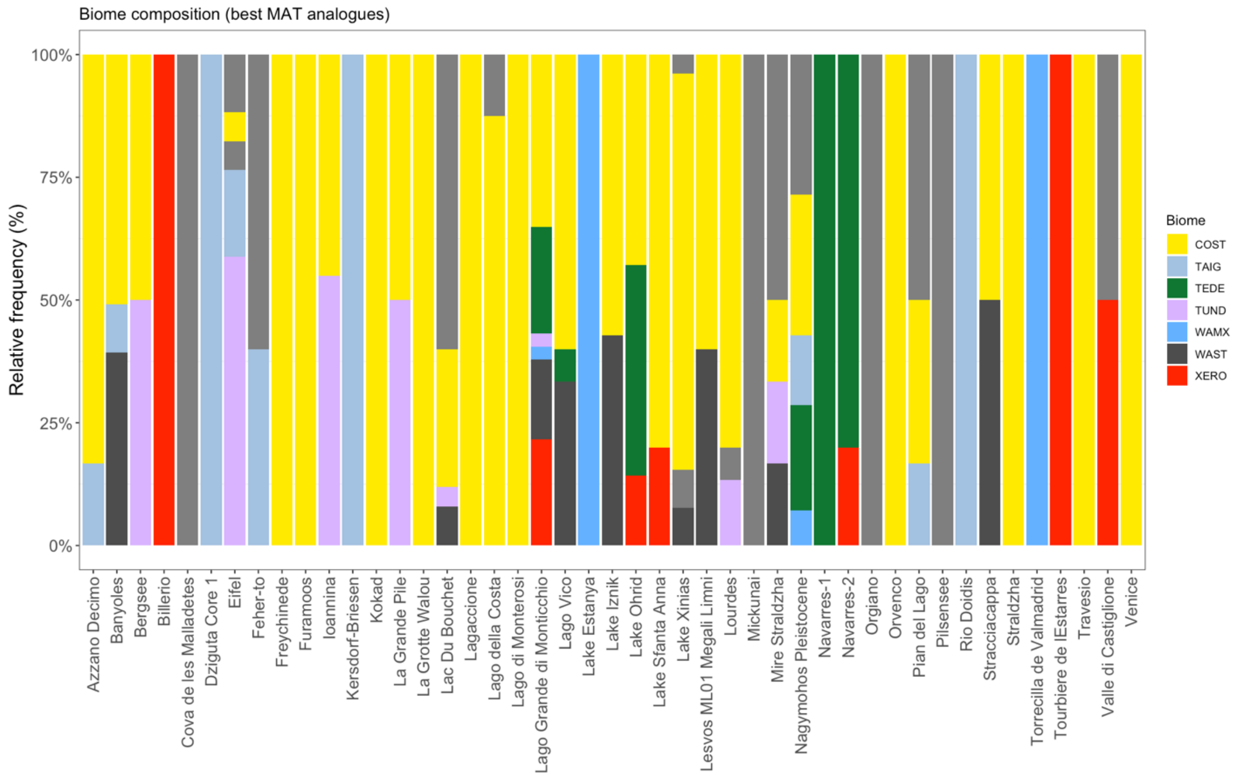


Figure R5. Cumulative histogram showing the distribution of best selected analogues assigned to biome classes, averaged by site. These analogues are obtained by comparison with LGM pollen assemblages (Table 1 of the manuscript).

2. *The reconstruction results of the three methods (MAT, WA-PLS, and CREST) based on pollen percentage data should also be presented somewhere.*

The reconstruction results obtained with the three methods based are presented in Section V.2 through Appendix 6, Figures 4–10, and Supplementary Material A. In Section V.3.1, the pollen-based climate reconstructions derived from the global calibration dataset are further compared with the pollen-derived reconstructions obtained from the (mega)biome calibrations.

Line 71: It should be "~23–19 thousand years ago" (use an en dash).

Corrected. Done

Line 347: More importantly, the authors should present how many age determinations (or dating points) are available for each record during the LGM.

The temporal resolution and chronological control of each pollen record are actually essential for interpreting the robustness of LGM reconstructions. All pollen sample ages were recalculated using these tie points and the corresponding sample depths, by applying Bayesian age-depth modelling in OxCal (Ramsey, 2017) with the IntCal20 calibration curve.

In particular for the potential revised manuscript, we have added in Table 1 information on the number of available radiocarbon ages within each sequence during the LGM interval. Done (number of LGM ages are given in bold in new Table 1).

Line 395: However, the impression of higher quality of modern analogues may be false when temporal resolution is reduced. The biome approach for climate reconstruction might be a last resort for very long-term pollen records.

We agree that the quality of modern analogues can be highly dependent on the temporal resolution, as well as the size/composition of the calibration dataset. As temporal resolution decreases and longer time windows are considered, the representativeness of individual modern analogues may become less robust. Apparent improvements in analogue quality may therefore be misleading due to scale-dependent effects in the reconstruction framework.

Guiot et al. (1993) - working on Holocene pollen and lake-level data from Europe - applied the biome approach of Prentice et al. (1992) to improve the interpretation of vegetation types (e.g., steppe versus tundra) and to better constrain associated climate reconstructions in situations where modern analogues may be limited. This illustrates that the choice of reconstruction strategy is closely linked to the temporal framework and the degree of agreement between fossil assemblages and modern vegetation-climate relationships.

More generally, for long pollen sequences, especially those extending beyond the Holocene, two complementary strategies can be considered to mitigate the lack of good analogues: (i) <u>a selective approach</u> based on a locally constrained calibration dataset that explicitly includes environments comparable to the fossil assemblages, and (ii) <u>a more exhaustive</u> approach using global calibration datasets combined with biome-based methods (e.g., biomisation or megabiomisation) to provide a more robust ecological grouping and improve interpretability of analogue relationships.

Guiot, J., Harrison, S., Prentice, I.C., 1993. Reconstructing of Holocene precipitation patterns in Europe using pollen and lake-level Data. Quat. Res. 40, 139–149. https://doi.org/10.1006/qres.1993.1066

**We clarified this point in the potential revised manuscript to emphasize that analogue quality and reconstruction strategies are scale-dependent, particularly when dealing with sparse or non-unique modern analogues in long-term records: "*Guiot et al. (1993) suggested using the biome approach of Prentice et al. (1992) to better distinguish between steppe and tundra environments, thereby improving the interpretation of fossil assemblages when good modern analogues are lacking. The scarcity of suitable modern analogues strongly depends on the temporal window considered for reconstruction, particularly during climatic periods characterized by vegetation compositions substantially different from those observed today." (line 319-323).*
**