

Response to the Editor and Referees 1 & 2 — Second Revision

We would like to thank the Editor and both Referees for the careful re-reading of the revised manuscript. We are pleased that both Referees have appreciated the revisions made in response to their comments and are satisfied with the first revision. We address below the single remaining comment raised by Referee 1 and endorsed by the Editor, concerning the clarification of the hyperparameter selection procedure for the number of retained spatial patterns. No further comments were raised by Referee 2.

Below, Referee 1 comment is reproduced in a sans serif font, and our response is provided below. Changes made in the manuscript are indicated where relevant.

Comment:

To reproduce the reported results, readers need clear guidance on how to choose the number of principal components (or retained spatial patterns) required to achieve satisfactory model performance. At present, I could only find the following statement in Section 3.5.1:

“For SPR, the number of retained spatial patterns is selected as a percentage (10%–90%) of the maximum available patterns, allowing a consistent search across regions of different sizes.”

This design choice is fundamental to the proposed methodology and has important implications for many potential applications. As such, it deserves a more thorough discussion.

For example, how is the optimal number of retained spatial patterns ultimately determined? Is the selected number fixed throughout the study period, or does it vary from one sample or time step to another? If it varies, what are the implications for users interested in climatological applications, such as estimating long-term trends or return values? More generally, does allowing the number of retained principal components to change across samples affect the statistical properties, consistency, or interpretability of the resulting predictions?

Response:

We thank the Referee for this important comment on reproducibility. We address the three aspects of the question in turn.

- **How is the optimal number of retained spatial patterns determined?** The number of retained patterns k is treated as a hyperparameter and selected by maximizing average RMSE performance on the validation set over the full interpolation period. The search is conducted over a grid of values ranging from 10% to 90% of the maximum number of available patterns, in steps of 5%. The optimal proportion varies across configurations and variables. For precipitation, it typically ranges from 20% to 60%, with values most commonly around 40%–50% under sparse network conditions (10%–30% density). For temperature variables, the optimal proportion is generally lower, ranging from 20% to 50% with most values around 25%–35%, reflecting the smoother and more structured spatial variability of temperature fields compared to precipitation.
- **Is the selected number fixed or does it vary across days?** The selected value of k is fixed once per experimental configuration — that is, for a given combination of region, region size, network density, and meteorological variable — and applied uniformly to all days of the interpolation period. It does not vary from one time step to another.
- **What are the implications for climatological applications?** The spatial patterns $\mathbf{V}_{p,k}^{\text{grid}}$ form a fixed orthonormal basis extracted once from the RCM auxiliary dataset. By construction, this basis does not vary in time — only the linear combination of its elements, captured through the daily regression coefficients $\hat{\beta}_k$, evolves from one time step to the next. The choice of k therefore determines the richness of the spatial basis available to represent the reconstructed fields, and is fixed per configuration to ensure that all time steps share the same spatial framework. This is particularly important for climatological applications such as estimating long-term trends or return values, where consistency of the reconstruction framework across time steps is essential. Varying k across time steps would imply reconstructing fields in spaces of different dimensions, making them structurally non-comparable and undermining any climatological analysis that requires temporal consistency.

The following text has been added to Section 3.5.1 (Hyperparameter selection):

For SPR, the number of retained spatial patterns k is treated as a hyperparameter and selected as a percentage (10%–90%) of the maximum available patterns, in steps of 5%, allowing a consistent search across regions of different sizes. The selected value of k is fixed once per experimental configuration — that is, for a given combination of region, region size, network density, and meteorological variable — and applied uniformly to all days of the interpolation period. This ensures that the reconstructed fields rely on a consistent spatial basis throughout, which is particularly important for climatological applications such as the estimation of long-term trends or return values, where consistency of the reconstruction framework across time steps is essential. The optimal proportion of retained patterns varies across configurations and variables. For precipitation, it typically ranges from 20% to 60%, with values most commonly around 40%–50% under sparse network conditions (10%–30% density). For temperature variables, the optimal proportion is generally lower, ranging from 20% to 50% with most values around 25%–35%, reflecting the smoother and more structured spatial variability of temperature fields compared to precipitation. These differences suggest that fewer spatial patterns are needed to capture the dominant spatial organization of temperature, while precipitation requires a richer basis to represent its more complex spatial structure.

Additional correction

In addition to the revisions described above, we corrected a minor factual error in the Code and Data Availability section. The ClimEx ensemble member identifier was incorrectly reported as `kcj` and has been corrected to `kdj`. This correction concerns documentation only and has no impact on the analyses, results, or conclusions presented in the manuscript.