Response to reviewer1

This study develops a three-dimensional perspective for characterizing Northern Hemisphere summer teleconnections by applying the conventional teleconnectivity method to the meridional and zonal vertical-circulation streamfunctions derived from the 3P-DGAC framework. Fourteen vertical-circulation teleconnection patterns are identified, and their associated horizontal circulation and surface air temperature signatures are examined. The study provides a potentially useful unified framework for connecting vertical circulation cells with several familiar horizontal teleconnection patterns, including the Silk Road Pattern, the British-Baikal Corridor, the British-Okhotsk Corridor, and the summer NAO. The reconstruction analyses further illustrate the diagnostic value of these patterns for Northern Hemisphere circulation and surface temperature variability.

Overall, I find the perspective interesting and potentially valuable. The principal contribution, in my view, is the provision of a unified three-dimensional framework through which both established and less familiar teleconnection structures can be examined. The manuscript is generally suitable for publication after minor revision. I have the following comments.

Response:

We sincerely thank the reviewer for the encouraging and constructive assessment of our work. The suggestions have been invaluable in improving the clarity and rigor of the manuscript. We have carefully addressed each comment raised by the reviewer, and our detailed responses are provided point by point below.

1. Robustness of the teleconnections identified near the pole

Several identified patterns, including HP and WCV, have one or both endpoints at very high latitudes. In some cases, the two endpoints also appear to be separated by a relatively short physical distance. Because meridians converge toward the pole, grid points that are well separated in longitude may nevertheless be geographically close. Moreover, the regular latitude-longitude grid strongly oversamples the polar cap in terms of grid-point density. These features raise the possibility that some of the identified pairs represent a local dipolar structure, spatial autocorrelation, or a gridding-related artefact rather than a genuine remote teleconnection. A brief sensitivity test using a reasonable minimum separation, an equal-area or latitude-weighted treatment, or exclusion of the immediate polar cap would help establish the robustness of these high-latitude patterns.

Response:

We thank the reviewer for highlighting the potential influence of meridian convergence and grid-point oversampling on teleconnection identification near the polar cap. We agree that the HP and WP patterns, whose endpoints are located within the polar cap, warrant particular scrutiny. We therefore performed a sensitivity analysis by excluding these two polar-cap patterns and repeating the subsequent SAT and GHT reconstruction analyses. The results show only a minor change in reconstruction consistency: the 44-year mean spatial correlations decrease from 0.64 to 0.63 for SAT and from 0.60 to 0.59 for GHT. For the 2022 extreme case, the corresponding correlations remain essentially unchanged (SAT: 0.75 vs. 0.75; GHT: 0.73 vs. 0.74) (Supporting Information Fig. S13; also presented as Fig. R1 in this letter for cross-reference). These results indicate that the principal reconstruction results are not sensitive to the inclusion of the two polar-cap patterns. We have added a brief description of this sensitivity test to Section 3.1 and provided the detailed results in Section 3.3 and the Supplementary Material. We retain all 14 patterns in the main analysis because they were identified using the same objective teleconnectivity criterion, while the sensitivity analysis demonstrates that the principal conclusions do not depend on the inclusion of the polar-cap patterns.

We fully agree with the reviewer that the polar patterns, along with several other newly identified patterns, merit further investigation. In future work, we plan to conduct detailed studies on the formation mechanisms and climate impacts of these 14 teleconnection patterns, particularly those that have not been previously documented, to further consolidate the three-dimensional circulation framework proposed in this study.

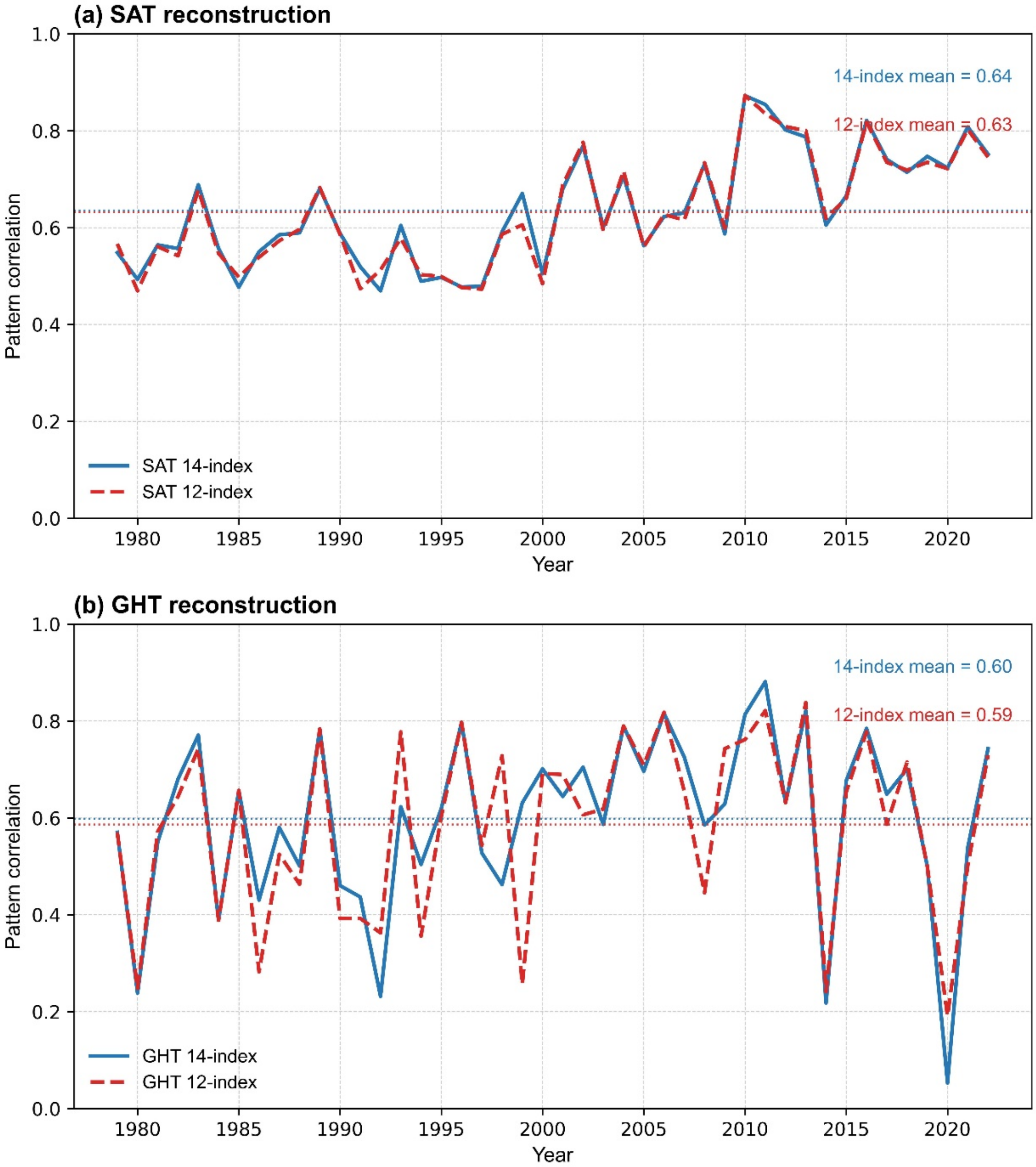

Figure R1 (Fig. S13). Sensitivity of reconstruction skill to the number of teleconnection indices. (a) Time series of spatial correlation coefficients between reconstructed and observed surface temperature anomalies for Northern Hemisphere summers (1979–2022) using 14 (solid) and 12 (dashed) teleconnection indices. (b) As in (a), but for geopotential height anomalies. Dashed horizontal lines represent the multi-decadal average values.

Accordingly, we have revised the manuscript as follows (see revised text in Section 3.1, lines 177–183; Section 3.3, lines 349–357; and Supplementary Material).

Lines 177–183:

The two polar patterns (HP and WP) involve endpoints within the polar cap, where meridian convergence and the resulting concentration of grid points may introduce potential uncertainties in teleconnection identification. To assess whether these high-latitude features materially affect our results, we repeated the subsequent reconstruction analyses after excluding HP and WP. The detailed sensitivity results are presented in Section 3.3 and the Supplementary Material. We retain the full set of 14 patterns in the main analysis because all patterns were identified using the same objective teleconnectivity criterion, while the sensitivity analysis provides an independent assessment of whether the polar patterns influence the principal conclusions.

Lines 349–357:

To assess the sensitivity of the reconstruction to the potential uncertainty associated with the polar patterns, we repeated the SAT and GHT reconstruction using only the 12 non-polar patterns, excluding HP and WP. The exclusion of the polar patterns results in only a minor reduction in the reconstruction consistency. The 44-year mean spatial correlations are 0.63 for SAT and 0.59 for GHT with the 12 patterns, compared with 0.64 and 0.60, respectively, using all 14 patterns (Fig. S13). For the 2022 extreme case, the spatial correlations remain essentially unchanged, with values of 0.75 for SAT and 0.73 for GHT using the 12 patterns, compared with 0.75 and 0.74, respectively, for the full set (Fig. S13). These results indicate that the main reconstruction results are not sensitive to the inclusion of the two polar-cap patterns. The polar patterns, like several *other newly identified patterns, warrant further investigation into their formation mechanisms to clarify their dynamical origins and physical significance.*

2. Nomenclature and relationship to established teleconnection patterns

The use of 14 geographically based abbreviations, such as WMCS, WWSJ, WGA, and WCV, makes the manuscript difficult to follow, especially when several indices appear together in the reconstruction analysis. The additional use of “HP” both for the Polar I pattern and as an abbreviation for “horizontal pattern” further increases the potential for confusion.

I recommend adding a summary table containing, for each pattern: its full name and abbreviation, whether it is based on (*H*) or (*W*), the coordinates of its two endpoints, and its closest previously established teleconnection counterpart. Where such a counterpart exists, the corresponding spatial correlation could also be included. This would allow readers to understand more clearly which patterns provide genuinely new information and which represent a three-dimensional reinterpretation of familiar modes.

Response:

We thank the reviewer for this constructive suggestion. We fully agree that the large number of geographically based abbreviations, together with the dual use of "HP," may hinder readability. To address this concern, we have made the following revisions.

First, we have replaced the generic abbreviation for "horizontal pattern" with HCP (standing for "horizontal circulation pattern") throughout the manuscript.

Second, we have added a comprehensive summary table (Manuscript Table 1; also presented as Table R1 in this letter for cross-reference) in Section 3.1, which lists for each of the 14 patterns: the abbreviation, full name, underlying stream function (*H* or *W*), endpoint coordinates, the correlation coefficient between the two poles, and the closest previously documented teleconnection counterpart. This table allows readers to quickly locate the definition of each pattern and to understand its relationship to established modes, if any, thereby clarifying which patterns represent three-dimensional reinterpretations of familiar modes and which may offer genuinely new information.

Table 1. Geographic names, endpoint coordinates, endpoint correlations, and analogous known patterns for the 14 vertical circulation teleconnections identified in this study.

Abbreviation	Full name	Pole A (lon, lat)	Pole B (lon, lat)	Correlation	Similar known pattern
HP	Polar I	(87.5°E, 87.5°N)	(95°W, 87.5°N)	-0.89	
HCB	Canadian-Bermuda	(100°W, 50°N)	(67.5°W, 42.5°N)	-0.76	ANA (0.69)
HCST	Caspian Sea-Tarim	(50°E, 45°N)	(82.5°E, 40°N)	-0.73	SRP (0.89)
HSK	Central Siberia-Kara Sea	(127.5°E, 60°N)	(75°E, 80°N)	-0.71	BBC (-0.77)
HGS	Greenland-Scandinavia	(40°W, 67.5°N)	(7.5°E, 62.5°N)	-0.68	
HBA	Black Sea-Aleutian	(30°E, 40°N)	(162.5°W, 57.5°N)	-0.68	
HUB	Ural-Baltic	(17.5°E, 52.5°N)	(57.5°E, 62.5°N)	-0.67	BOC (0.74)
WP	Polar II	(12.5°W, 87.5°N)	(167.5°E, 87.5°N)	-0.90	
WMCS	Mongolia-Central Siberia	(107.5°E, 42.5°N)	(100°E, 67.5°N)	-0.77	
WWSJ	West Siberian-Junggar	(77.5°E, 65°N)	(87.5°E, 45°N)	-0.74	
WGA	Greenland Sea-Azores	(5°W, 70°N)	(20°W, 45°N)	-0.76	SNAO (-0.67)
WOM	Ogasawara-Mexico	(155°E, 25°N)	(95°W, 25°N)	-0.75	
WCV	Chukchi Sea-Victoria	(172.5°W,80°N)	(102.5°W, 70°N)	-0.72	
WBA	Bering Strait-Aleutian	(162.5°W, 70°N)	(155°W, 50°N)	-0.70	

Note: SRP, BBC, BOC, and SNAO denote the Silk Road Pattern, British-Baikal Corridor, British-Okhotsk Corridor, and summer North Atlantic Oscillation, respectively. References: SRP (Enomoto et al., 2003; Lu et al., 2002); BBC and BOC (Xu et al., 2019b, 2022); SNAO (Greatbatch and Rong, 2006).

3. Dependence and possible redundancy among the 14 indices

The 14 patterns are identified separately from the (*H*) and (*W*) stream functions and are not constrained to be mathematically orthogonal. It is therefore important to establish whether some indices describe closely related aspects of the same underlying circulation variability. This issue is also relevant to the subsequent stepwise regression and reconstruction analyses.

The authors should provide, at minimum, a correlation matrix among the 14 indices and discuss any substantial dependence or clustering among them. It would also be useful to clarify whether the (*H*)- and (*W*)-based patterns can be regarded as distinct modes or, in some cases, as different projections of the same three-dimensional circulation system. The manuscript should avoid implying that all 14 patterns are dynamically independent unless this can be demonstrated.

Response:

We thank the reviewer for this important methodological concern. Following the reviewer's suggestion, we have computed the correlation matrix among the 14 indices and added a discussion of their inter-relationships in the Discussion section (see lines 418–431; Fig. S14, also presented as Figure R2 in this letter for cross-reference).

The correlation matrix confirms that the indices are not strictly orthogonal, with several pairs exhibiting notable correlations. For instance, the correlation between HCSTI and HUBI ($r = -0.51$) may reflect the documented occasional coupling between the Silk Road Pattern and the British–Okhotsk Corridor (Xu et al., 2022). Other correlated pairs, particularly between H-based and W-based patterns, may represent different projections of the same three-dimensional circulation system. These inter-correlations suggest that some of the indices share common underlying variability, which is not unexpected given that the real atmosphere is inherently coupled across different circulation components.

We acknowledge that these correlations indicate some degree of interdependence among the patterns. However, the presence of such correlations does not undermine the utility of the full set of indices. First, the reconstruction of SAT and circulation fields does not require the indices to be orthogonal; it only requires that their collective superposition captures the dominant variability. Second, the stepwise regression employed in the SAT reconstruction inherently accounts for multicollinearity by selecting only the most significant and independent predictors at each step. We have revised the wording throughout the manuscript to avoid implying that all 14 patterns are dynamically independent.

We have added a dedicated paragraph in the Discussion section to address this point, and the correlation matrix is now presented as Fig. S14 in the Supplementary Material.

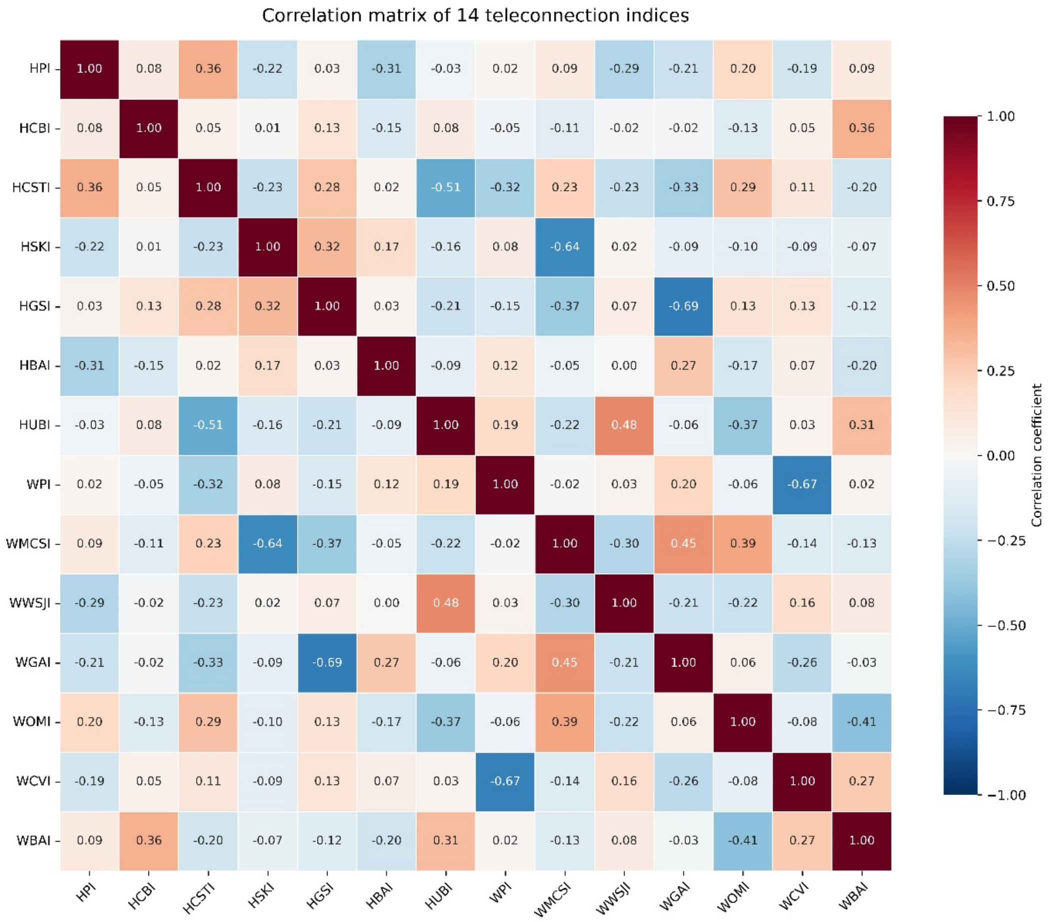

Figure R2 (Fig. S14). Correlation heatmap of 14 teleconnection indices.

The paragraph we added to the Discussion section (Lines 418–431) is as follows:

A practical consideration concerns the inter-relationships among the 14 indices. As shown in Fig. S14, the indices are not strictly orthogonal, with several pairs exhibiting notable correlations. For instance, the correlation between HCSTI and HUBI (r = −0.51) may reflect the documented occasional coupling between the Silk Road Pattern and the British–Okhotsk Corridor (Xu et al., 2022). Other correlated pairs, particularly between H-based and W-based patterns, may represent different projections of the same three-dimensional circulation system. These inter-correlations suggest that some of the indices share common underlying variability, which is not unexpected given that the real atmosphere is inherently coupled across different circulation components. However, the presence of such correlations does not undermine the utility of the full set of indices for two reasons. First, the reconstruction of SAT and circulation fields does not require the indices to be orthogonal; it only requires that their collective superposition captures the dominant variability. Second, the stepwise regression employed in the SAT reconstruction inherently accounts for multicollinearity by selecting only the most significant and independent predictors at each step. The focus of this study is to introduce the three-dimensional framework and demonstrate its diagnostic value, rather than to systematically examine the independence of each pattern. Nevertheless, the detailed coupling mechanisms and physical linkages among these teleconnection patterns warrant further investigation in future work.

4. Out-of-sample robustness of the reconstruction

The teleconnection patterns, regression coefficients, predictor selection, and reconstruction skill appear to be derived and evaluated over essentially the same 1979-2022 period. The reported spatial correlations may therefore partly reflect in-sample fitting, particularly given the relatively short record and the use of stepwise regression with 14 potential predictors.

A leave-one-year-out or comparable cross-validation would provide a more convincing estimate of reconstruction skill for both SAT and circulation anomalies. At least the 2022 reconstruction should be performed without using 2022 in the estimation of the regression coefficients. If redefining the complete teleconnection patterns within every training sample is impractical, the authors should clearly distinguish between pattern definition and regression fitting and acknowledge the remaining in-sample component of the analysis.

Response:

We thank the reviewer for this rigorous methodological concern. Following the reviewer's suggestion, we performed a leave-one-year-out cross-validation (LOOCV) for the SAT reconstruction, in which the regression coefficients for each target year were estimated using the remaining 43 years.

The results confirm the robustness of our reconstruction framework. The original 44-year mean spatial correlation between reconstructed and observed SAT anomalies is 0.64 (Fig. S6). The LOOCV yields an average correlation of 0.57 over the same period, confirming that the reconstruction skill is not merely a result of in-sample fitting. Particularly during extreme heat years (e.g., 2016, 2018, 2019, 2021, and 2022), the spatial correlations exceed 0.75 in the original reconstruction, with a LOOCV average of 0.71, highlighting the robust capability of these patterns in reproducing hemispheric-scale temperature extremes even under cross-validation (Fig. S6, also presented as Figure R3 in this letter for cross-reference). For the 2022 circulation reconstruction, the LOOCV spatial correlation is 0.63, which is lower than the in-sample estimate of 0.74 but remains statistically significant ($p < 0.05$), indicating that the major anomaly centers are still captured (Fig. R4).

We acknowledge that a portion of the reported skill reflects in-sample fitting. We have therefore revised the manuscript to clearly distinguish between the pattern identification (performed on the full period) and the regression fitting, and to explicitly state that the cross-validation provides a more conservative estimate of predictive skill. These revisions have been incorporated into Section 3.3.1 (see lines 305–310).

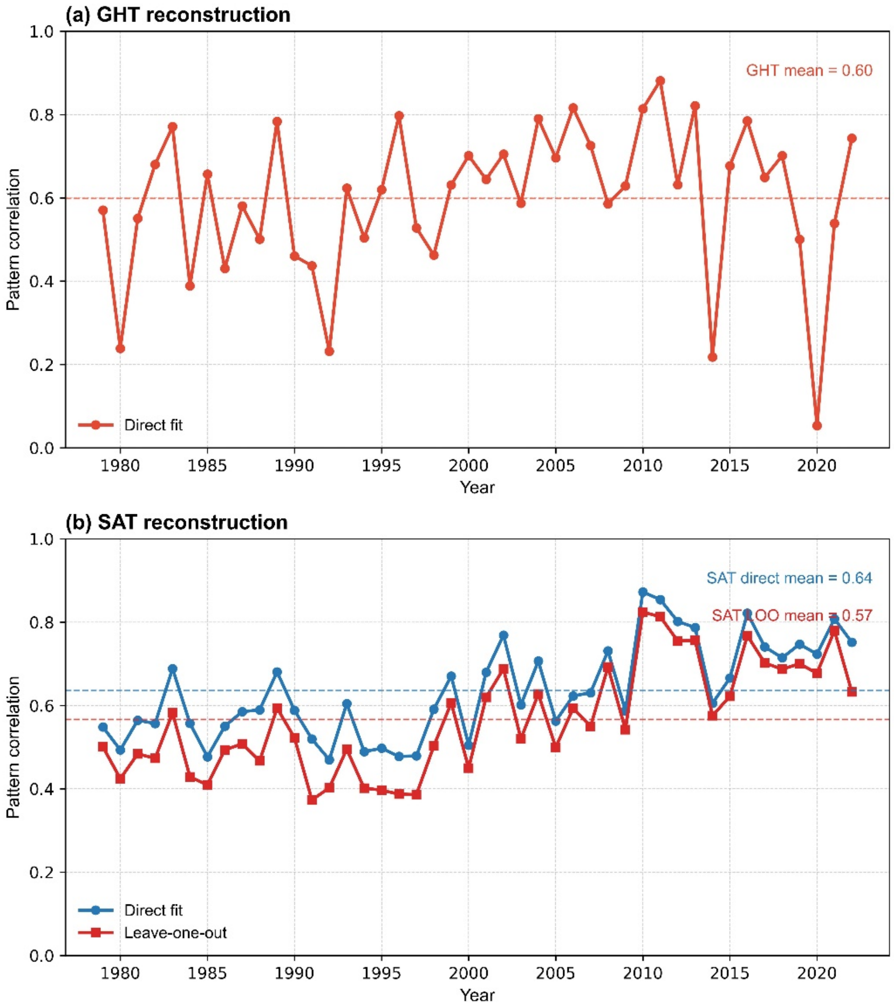

Figure R3 (Fig. S6). Leave-one-out reconstruction skill of summer climate variability. (a) Time series of spatial correlation coefficients between leave-one-out reconstructed and observed surface temperature anomalies for Northern Hemisphere summers (1979–2022). (b) As in (a), but for geopotential height anomalies. Solid and dashed lines represent direct-fit and leave-one-out reconstruction results, respectively; dashed horizontal lines represent the average values.

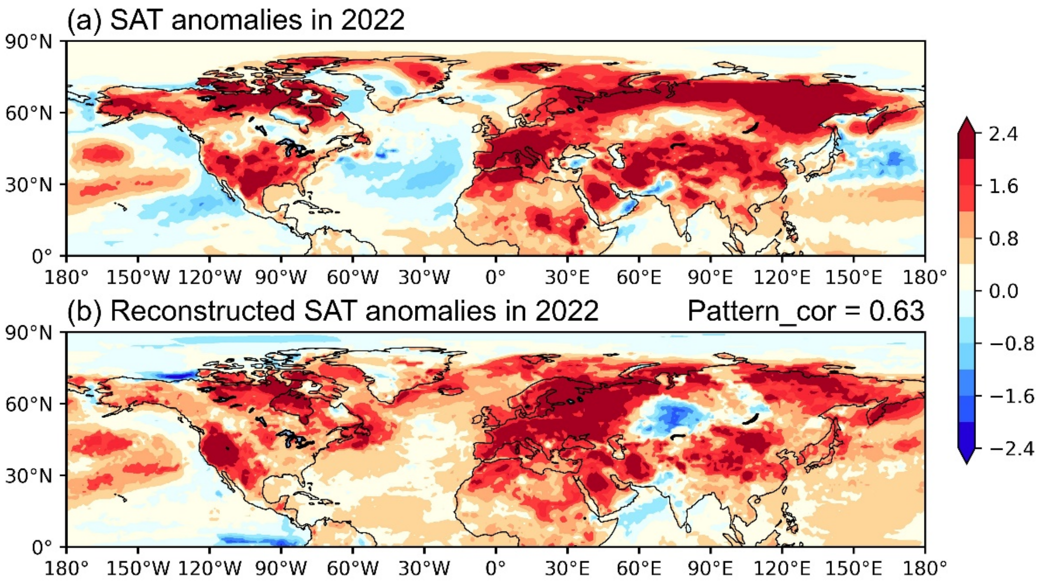

Figure R4. Leave-one-out reconstruction of the 2022 Northern Hemisphere summer surface temperature anomaly. (a) Observed summer surface air temperature anomalies in 2022. (b) Leave-one-out reconstructed surface air temperature anomalies in 2022, obtained by fitting the regression model over 1979–2021 and then applying the model to the 2022 teleconnection indices. The spatial correlation coefficient between the observed and reconstructed fields is indicated in the panel.

5. Potential application to seasonal prediction

The demonstrated relationship between these modes and Northern Hemisphere summer SAT raises an interesting question regarding their practical predictability. Can seasonal forecast systems predict the amplitudes of these three-dimensional teleconnection indices, and would an index-based reconstruction provide useful SAT prediction skill beyond the model climatology or conventional circulation indices?

A full forecast experiment may be beyond the scope of the present revision. Nevertheless, the authors could provide a preliminary assessment using an available seasonal hindcast dataset, if feasible, or otherwise expand the discussion to formulate this as a concrete future application. In the absence of a hindcast evaluation, statements that improved representation of these modes would enhance forecasting skill should be appropriately qualified as a hypothesis rather than a demonstrated result.

Response:

We thank the reviewer for this constructive and forward-looking suggestion. We fully agree that while the diagnostic utility of our framework is demonstrated, its potential for practical seasonal prediction remains to be tested and should not be overstated.

Accordingly, we have revised the final paragraph of the Discussion section to clearly frame the predictive application as a hypothesis and a future research direction, rather than a demonstrated result. The revised text (see line 445–453) reads as follows:

Finally, the demonstrated diagnostic utility of these three-dimensional teleconnection indices raises the question of whether they might also offer some predictability for regional summer climate. A logical next step would be to examine whether operational seasonal forecast systems are capable of predicting the amplitudes of these indices, and whether a reconstruction based on these indices could provide additional forecasting skill beyond that derived from models or conventional circulation indices. Should this prove to be the case, incorporating these dynamically grounded indices as predictors *into sub-seasonal to seasonal (S2S) prediction frameworks or data-driven machine learning models may contribute to improved forecasts of regional persistent heatwaves. This possibility, however, remains to be rigorously evaluated through out-of-sample validation in future work.*

In this revision, we explicitly acknowledge that the predictive utility of these indices has not yet been evaluated, and we frame the potential improvement in forecasting skill as conditional ("Should this prove to be the case") and requiring rigorous future validation. These revisions have been incorporated into the Discussion section (see lines 445–453).

6. Consistency and presentation

Several internal inconsistencies should be corrected during revision. For example, 1979-2022 contains 44 summers, whereas the manuscript refers to a “43-year mean spatial correlation.” Figure 5 gives 1979-2018 in its caption, although the main analysis period is stated as 1979-2022. The ordering of the (W)-based patterns in some figure captions also appears inconsistent with the panel labels and the discussion in the text. The reference to HP-HUB in Fig. 2b should be checked, as this pattern appears to be shown in another panel. Finally, the description of the manuscript structure at the end of the Introduction does not match the actual section numbering. A careful proofreading of the pattern names, panel references, duplicated words, and analysis periods is needed.

Response:

We thank the reviewer for carefully identifying these inconsistencies. We have thoroughly proofread the entire manuscript and corrected all the issues noted by the reviewer. Specifically, we have corrected the "43-year" to "44-year" throughout the text, revised the Figure 5 caption to 1979–2022, unified the ordering of W-based patterns in all figure captions to match the panel labels and text, verified and corrected the panel reference for HUB, and updated the description of the manuscript structure at the end of the Introduction to align with the actual section numbering. In addition, we have carefully checked the pattern names, panel references, duplicated words, and analysis periods throughout the manuscript to ensure consistency. We believe these corrections have improved the clarity and accuracy of the presentation.