

Reply to RC1:

General comments:

This manuscript investigates the interannual variability of North American spring temperature evolution using Season-reliant Empirical Orthogonal Function (S-EOF) analysis. Two leading S-EOF modes, characterized by persistent and temporally reversing monthly temperature anomalies, are identified. The authors further explore the physical mechanisms associated with these modes, highlighting the roles of tropical sea surface temperature (SST) evolution from winter to spring and midlatitude circulation anomalies through both Atlantic and Pacific pathways. A dominance analysis is also conducted to quantify the relative contributions of tropical SST variability and midlatitude circulation.

Overall, the manuscript is well written and presents a novel perspective on North American spring temperature variability by focusing on its subseasonal evolution rather than the seasonal mean alone. This study also provides valuable insights into how tropical SST variability and midlatitude circulation jointly shape distinct spring temperature evolution patterns. Several comments and suggestions are provided below, which I believe will help improve the clarity and robustness of the manuscript.

Reply:

Thank you for your thoughtful and constructive comments, which have greatly helped us improve the manuscript. We have carefully revised the manuscript to address the comments and suggestions raised by the reviewer. Please see our point-by-point responses below for details.

Specific comments:

1. In the Introduction, the authors highlight links between spring temperature variability and hydrological processes. This raises the question of whether the two identified S-EOF modes are associated with distinct hydrological processes. Based on Fig. 3, S-EOF1 appears to be characterized by a local intensification of temperature anomalies over North America from winter to spring, whereas S-EOF2 is associated with transitions in temperature anomalies. It would be interesting to further examine the evolution of snow cover and soil moisture anomalies associated with these two modes. Such analyses could help clarify the potential roles of snow–albedo feedback and land–atmosphere interactions in shaping the observed temperature evolution patterns.

Reply:

Thank you for this helpful suggestion. We have further examined the evolution of snowfall (Fig. R1), surface albedo (Fig. R2), and soil moisture (Fig. R3) anomalies associated with the two S-EOF modes. The results indicate that S-EOF1 is linked to snowfall anomalies over western Canada in the preceding winter (Fig. R1a). The subsequent evolution of snowfall and surface albedo anomalies (Figs. R1a–d and R2a–d) suggests a potential positive snow–albedo feedback that may contribute to the persistence of the temperature pattern over North America. In contrast, S-EOF2 is not associated with obvious snowfall anomalies in the preceding winter (Fig. R1e). Neither

mode exhibits significant linkages with preceding soil moisture anomalies (Figs. R3a and R3e), while simultaneous soil moisture anomalies show a less coherent relationship with the temperature evolution (Figs. R3b–d and R3f–h), likely reflecting the influence of other physical processes.

We have included a corresponding discussion of these results in the revised manuscript. **Please see Lines 378–383 in the tracked-changes version of the manuscript (hereafter the same).**

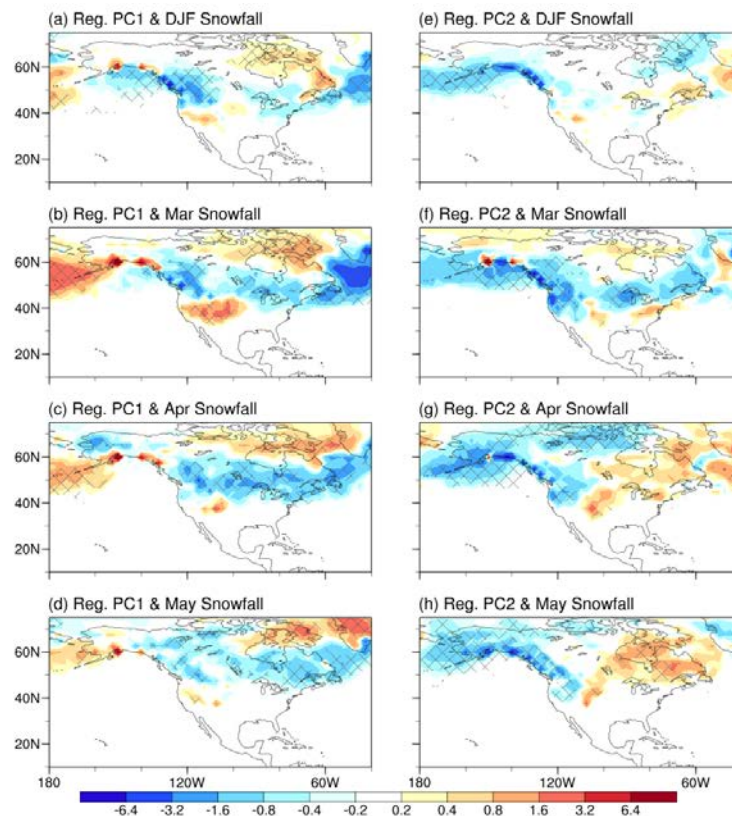


Figure R1: (a) Winter-mean snowfall anomalies (shading; unit: 0.1 mm per standard deviation of PC) regressed onto the standardized PC1. All fields are linearly detrended prior to regression. Cross-hatching indicates regions where the regressed snowfall anomalies are significant at the 95% confidence level based on a two-tailed Student's *t* test. (b–d) Same as (a), but for snowfall anomalies in (b) March, (c) April, and (d) May. (e–h) Same as (a–d), but for snowfall anomalies regressed onto the standardized PC2.

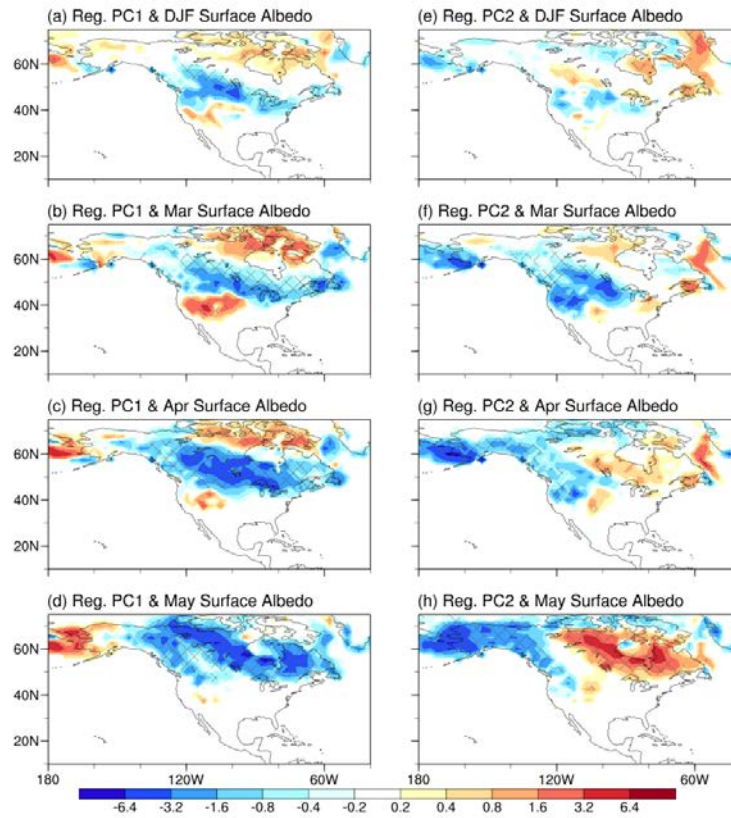


Figure R2: (a) Winter-mean surface albedo anomalies (shading; unit: % per standard deviation of PC) regressed onto the standardized PC1. All fields are linearly detrended prior to regression. Cross-hatching indicates regions where the regressed surface albedo anomalies are significant at the 95% confidence level based on a two-tailed Student's t test. (b–d) Same as (a), but for surface albedo anomalies in (b) March, (c) April, and (d) May. (e–h) Same as (a–d), but for surface albedo anomalies regressed onto the standardized PC2.

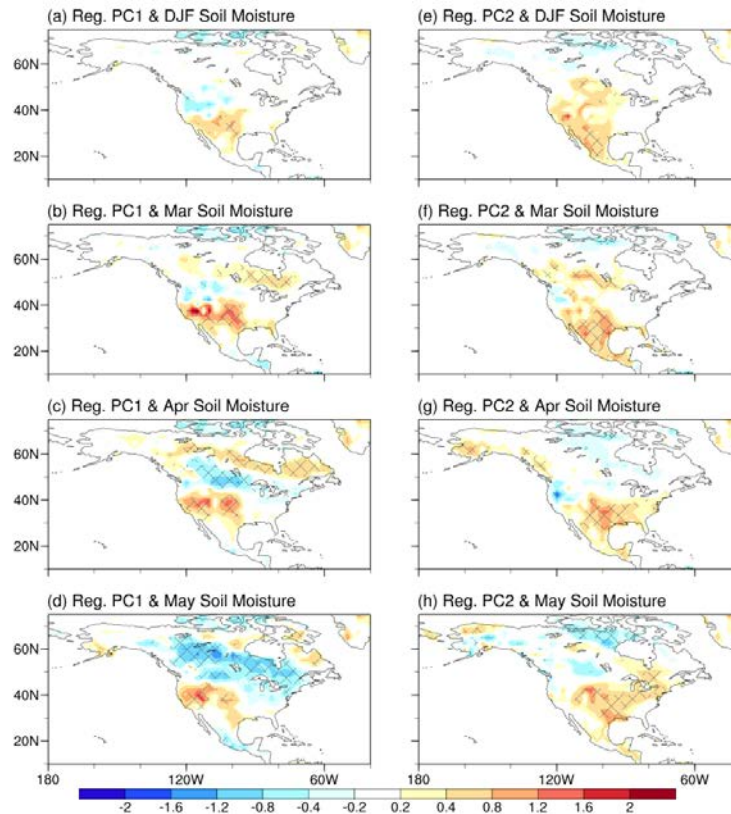


Figure R3: (a) Winter-mean soil moisture anomalies (shading; unit: mm per standard deviation of PC) regressed onto the standardized PC1. Soil moisture is calculated from volumetric soil water in the first soil layer (0–7 cm) by multiplying by the layer thickness. All fields are linearly detrended prior to regression. Cross-hatching indicates regions where the regressed soil moisture anomalies are significant at the 95% confidence level based on a two-tailed Student's t test. (b–d) Same as (a), but for soil moisture anomalies in (b) March, (c) April, and (d) May. (e–h) Same as (a–d), but for soil moisture anomalies regressed onto the standardized PC2.

2. Although the focus of this study is North America, it is interesting to note that temperature anomalies over Eurasia also exhibit distinct subseasonal evolution. This point is not explicitly discussed in the manuscript, although Eurasia appears to be included in most figures. I therefore suggest adding a brief discussion to clarify the co-occurrence of spring temperature evolution over Eurasia and North America.

Reply:

Thank you for your comment. We agree that the temperature anomalies over Eurasia also exhibit distinct subseasonal evolution associated with the two S-EOF modes, particularly in March, when the two modes are accompanied by opposite phases of the NAO. We have therefore added a brief discussion in the revised manuscript to highlight the co-occurrence of temperature evolution over Eurasia and North America and its association with large-scale atmospheric circulation, while noting that a detailed investigation of the Eurasian temperature evolution and its underlying mechanisms is beyond the scope of this study. **Please see Lines 372–377.**

3. From the Hovmöller diagrams of tropical SST anomalies associated with these two modes, S-EOF1 appears to be related to the development of Eastern Pacific (EP) ENSO that peaks in early winter, whereas S-EOF2 is linked to a more persistent Central Pacific (CP) ENSO. I suggest further analyzing the potential linkages between these modes and the distinct EP/CP ENSO flavors. In addition, SST anomalies over the Indian Ocean also exhibit distinct characteristics. It would be helpful to briefly discuss this region and consider adding relevant indices, such as the Indian Ocean Dipole (IOD), to Table 1 for completeness.

Reply:

Thank you for your thoughtful comments. We have further investigated the potential linkages between the two S-EOF modes and EP/CP ENSO, as well as the IOD (Table R1).

We find that winter EP (CP) ENSO is significantly correlated with PC1 (PC2), as shown in Fig. R4 and Table R1. We also note that EP and CP ENSO are associated with the spring NPO and NP patterns, respectively (Table R1), which have been shown to play important roles in shaping S-EOF1 and S-EOF2. This raises the possibility that the influences of EP and CP ENSO on North American spring temperature anomalies may be partly mediated through their respective relationships with the NPO and NP patterns.

To further examine this possibility, we repeated the dominance analysis by replacing the winter Niño3.4 index with the winter EP and CP ENSO indices (Fig. R5). The results support an important role of CP ENSO in S-EOF2, whereas no comparably strong contribution of EP ENSO is identified for S-EOF1. Further investigation suggests that the apparent EP ENSO–NPO relationship is strongly influenced by two extreme EP ENSO years, 1983 and 1998, in which the EP ENSO index exceeds 4 standard deviations (Fig. R4a). After excluding these two years, the correlation between the EP ENSO index and the spring NPO index is no longer statistically significant (Table R1). This indicates that the apparent preferential linkage between EP ENSO and NPO is not robust and depends strongly on a few extreme EP ENSO events. Therefore, although a potential role of EP ENSO cannot be ruled out, the significant EP ENSO–PC1 relationship does not necessarily imply that its influence on S-EOF1 is strongly mediated through the spring NPO and should be interpreted with caution. In contrast, the relationship between CP ENSO and the NP pattern is more consistent with the dominance analysis, suggesting that CP ENSO may contribute to S-EOF2 partly through its connection with the NP pattern (Figs. R5b, 5d).

Regarding the relationships between the IOD and the two S-EOF modes, we find that only the spring IOD index is significantly correlated with PC1 ($r = 0.26$; Table R1). Interestingly, the spring IOD index is also significantly correlated with the spring NPO index ($r = 0.31$; Table R1). Although this simultaneous relationship does not imply causality, previous studies have shown that Indian Ocean variability can modulate tropical Pacific SST evolution through subtropical Pacific processes in which the NPO also plays an important role (Lin and Yu, 2024). Given the close relationship between the NPO and S-EOF1, the co-variability between the spring IOD and NPO may therefore provide a potential pathway linking Indian Ocean variability to S-EOF1, although the underlying physical mechanisms require further investigation.

Accordingly, we have expanded Table 1 in the revised manuscript to include the EP/CP ENSO and IOD indices, revised the discussion in Section 3.2, and repeated the dominance analysis by incorporating the EP/CP ENSO and IOD indices (Fig. 9 in the revised manuscript).

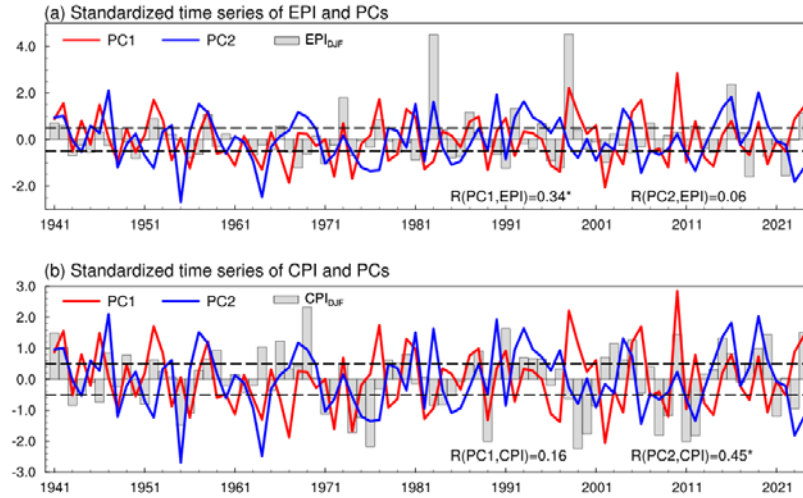


Figure R4: (a) Standardized time series of the EP ENSO index (EPI; bars) and the PCs of S-EOF1 (PC1; red line) and S-EOF2 (PC2; blue line). Horizontal dashed lines denote ± 0.5 standard deviations. Numbers at the bottom of panel (a) indicate the correlation coefficients between the PCs and the EPI. (b) Same as (a), but for standardized time series of the CP ENSO index (CPI; bars) and the PCs. Numbers at the bottom of panel (b) indicate the correlation coefficients between the PCs and the CPI. The EPI and CPI are derived from the first two EOF modes of winter-mean SST anomalies over the equatorial Pacific (15°S – 15°N , 140°E – 80°W). The EPI is defined as $(\text{SST-PC1} - \text{SST-PC2})/\sqrt{2}$, while the CPI is defined as $(\text{SST-PC1} + \text{SST-PC2})/\sqrt{2}$, where SST-PC1 and SST-PC2 are the standardized PCs of the first two SST EOF modes (Geng et al., 2022; Takahashi et al., 2011).

Table R1 Correlation coefficients of the EPI, CPI, and the winter and spring IOD indices with PC1, PC2, and selected climate indices, including the winter and spring Niño3.4 indices, the spring TNA index, the spring NPO index, the spring NP index, and the early spring (March) NAO index. For the EPI, values in parentheses indicate the correlation coefficients after excluding the two years with EPI values exceeding 4 standard deviations. All indices are standardized and linearly detrended. Correlations significant at the 95% confidence level based on a two-tailed Student's *t* test are shown in bold.

	PC1	PC2	Niño3.4 (DJF)	Niño3.4 (MAM)	TNA (MAM)	NPO (MAM)	NP (MAM)	NAO (Mar)
EPI	0.34 (0.39)	0.06 (-0.02)	0.67 (0.61)	0.53 (0.46)	0.29 (0.30)	0.35 (0.21)	0.08 (0.01)	0.10 (0.03)
CPI	0.16	0.45	0.71	0.61	0.46	-0.13	0.22	0.03
IOD (DJF)	0.17	-0.06	0.12	0.05	0.21	0.21	-0.07	-0.14
IOD (MAM)	0.26	-0.16	-0.10	-0.01	0.06	0.31	-0.03	-0.11

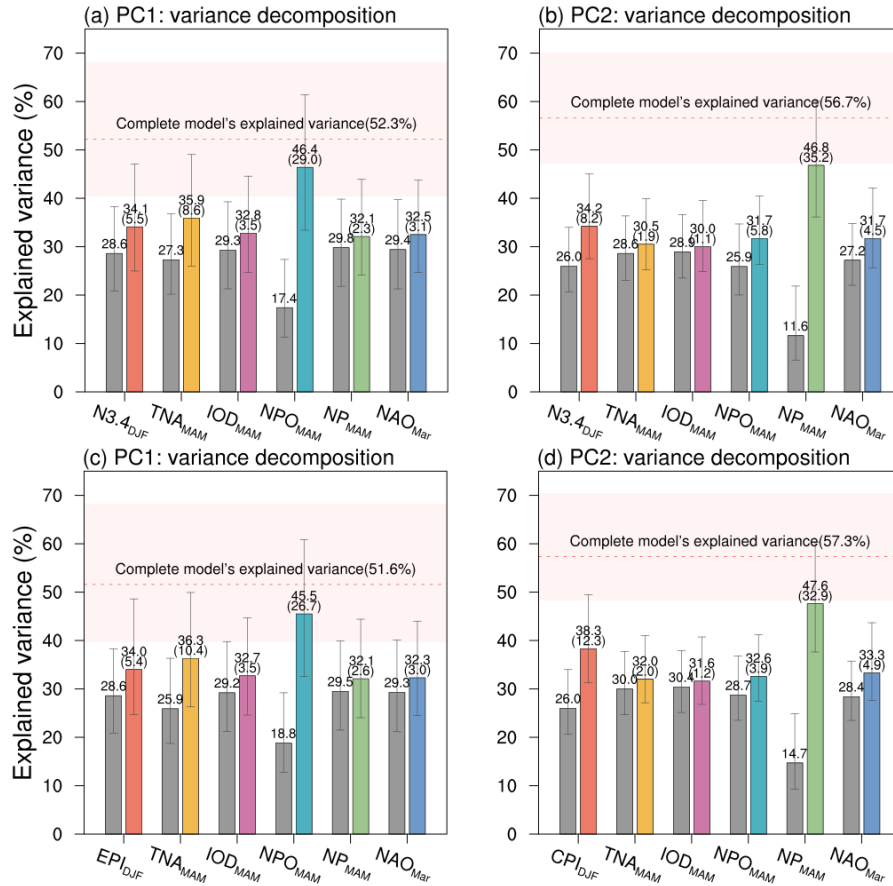


Figure R5: (a–b) Variance decomposition (dominance analysis) for **(a)** PC1 and **(b)** PC2, using the winter Niño3.4 index, the spring TNA index, the spring IOD index, the spring NPO index, the spring NP index, and the early spring NAO index. **(c–d)** As in **(a–b)**, but with the winter Niño3.4 index replaced by the winter EPI for **(c)** PC1 and by the winter CPI for **(d)** PC2. Gray bars denote the weighted-average R^2 of models excluding a given variable (32 combinations), while colored bars denote the weighted-average R^2 after including that variable (another 32 combinations). Values above the gray (colored) bars indicate the R^2 before (after) including each variable, with the corresponding incremental contributions shown in parentheses above the colored bars. Error bars on the gray and colored bars indicate the 5th and 95th percentiles of the bootstrap distributions based on 10,000 resamples of years. The red dashed line represents the R^2 of the complete model, corresponding to the sum of the contributions from all individual variables, and the red shading indicates its 5th–95th percentile bootstrap range. See Methods for details of the dominance analysis and bootstrap procedure.

- The authors argue that the early spring NAO plays an important role in regulating tropical North Atlantic SST responses to winter ENSO. However, the physical mechanisms responsible for the occurrence of opposing NAO phases remain unclear. Do they arise from internal atmospheric variability, or are they related to differences in ENSO decay rates or influences from other ocean basins?

Reply:

Thank you for this important comment. Based on our analysis, we do not find a significant relationship between the March NAO and ENSO (Table 1 in the manuscript)

or IOD (Table R1). These results suggest that the occurrence of opposite NAO phases is not closely related to differences in these tropical SST forcings, and may instead reflect, at least in part, internal atmospheric variability.

We also note that the significant simultaneous relationship between the March NAO and tropical North Atlantic SST anomalies (Fig. 6d in the manuscript) indicates a close coupling between North Atlantic atmospheric circulation and tropical Atlantic SST variability, consistent with previous studies (Chen et al., 2021; Ding et al., 2023; Tian et al., 2025; Xie and Carton, 2004; Zhang and Jiang, 2023). However, this simultaneous relationship alone does not establish causality. Therefore, while our results support an important connection between the March NAO and the contrasting tropical North Atlantic SST evolution following winter ENSO, the physical origin of the opposite NAO phases remains unclear. We have clarified these issues in the revised manuscript. **Please see Lines 360–365.**

5. Dominance analysis appears to be a useful tool for separating the contributions of correlated climate indices. However, interpreting the estimated contributions as deterministic values may be problematic, as the relationships between these modes and the associated climate indices can vary over time. In this regard, the bootstrapped results presented in the supplement provide a more robust assessment of the uncertainties. However, additional details on the bootstrap procedure should be provided. Given their importance, I suggest that these results be included in the main text. In addition, if feasible, the authors may consider incorporating climate model simulations to further evaluate the robustness and reliability of the dominance analysis results.

Reply:

Thank you for these helpful suggestions. We have revised Figure 9 in the manuscript to explicitly show the uncertainty ranges of the dominance analysis; the revised figure is also shown below as Figure R6. We have also added details of the bootstrap procedure to the Data and Methods section. **Please see Lines 135–138.** Specifically, years are randomly resampled with replacement while maintaining the same sample size as the original analysis period (84 years). The complete dominance analysis is then repeated for each of 10,000 bootstrap samples, and the 5th and 95th percentiles of the resulting distributions are used to quantify the uncertainty in the explained variance before and after including each variable.

The bootstrap results further support the robust contributions of the key atmospheric circulation indices discussed in the manuscript. In particular, for S-EOF1, the bootstrap uncertainty ranges of the averaged explained variance before and after including the NPO index are well separated. A similarly clear separation is found for the NP index in S-EOF2. These results indicate that the contributions of the NPO to S-EOF1 and the NP to S-EOF2 are robust to resampling of the analysis years, rather than being determined by a limited subset of years. A detailed discussion of the bootstrap results has been added to Section 3.3 of the revised manuscript.

We also appreciate the reviewer's suggestion to further evaluate these relationships using climate model simulations. The present study focuses on diagnosing North

American spring temperature evolution and its associated physical processes using observational and reanalysis datasets. A rigorous model-based assessment would additionally require evaluating whether climate models can realistically reproduce the two S-EOF modes and their associated physical processes, which is beyond the scope of the present study. We therefore leave a systematic evaluation using climate model simulations for future work, as noted in the revised manuscript (see Lines 389–390).

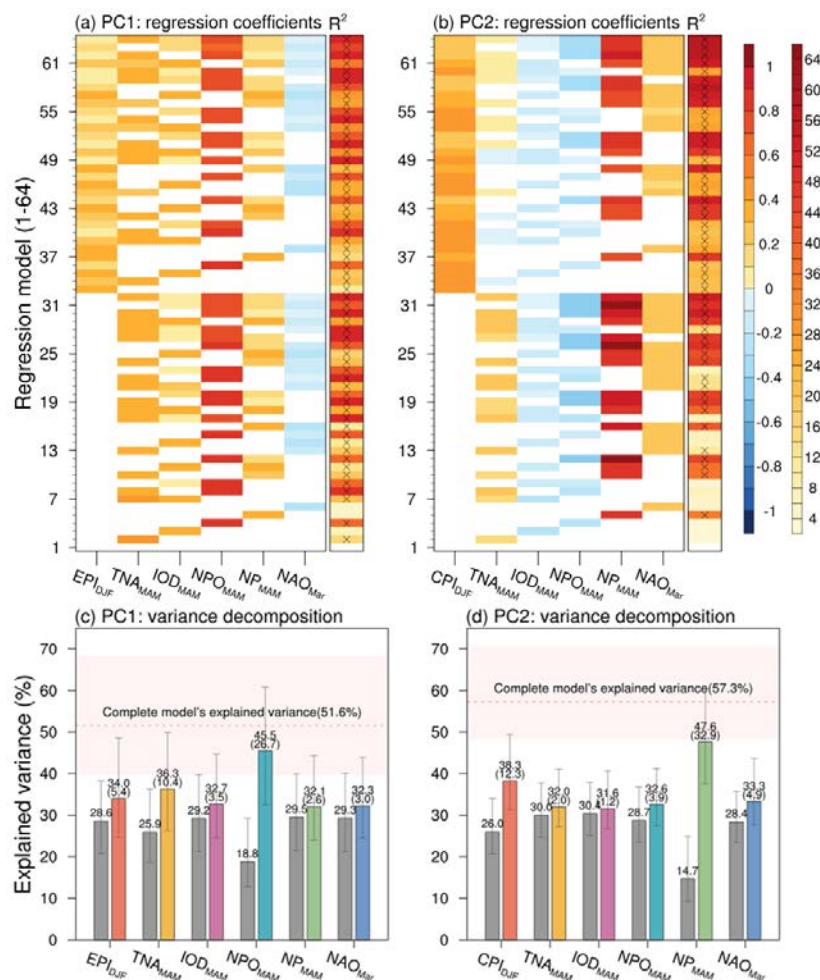


Figure R6: (a–b) Heatmaps of regression coefficients (first six columns) and explained variance (R^2 , seventh column, unit: %) for all subset regression models of **(a)** PC1 and **(b)** PC2, constructed from different combinations of the winter EPI (for PC1)/CPI (for PC2), the spring TNA index, the spring IOD index, the spring NPO index, the spring NP index, and the early spring NAO index. All indices are standardized and linearly detrended. Model 1 corresponds to the null model (no variables) and is included as a baseline. The cross marks in the seventh column indicate that the corresponding regression models are statistically significant at the 95% confidence level based on a two-tailed Student's t test. **(c–d)** Variance decomposition (dominance analysis) for **(c)** PC1 and **(d)** PC2, using the winter EPI (for PC1)/CPI (for PC2), the spring TNA index, the spring IOD index, the spring NPO index, the spring NP index, and the early spring NAO index. Gray bars denote the weighted-average R^2 of models excluding a given variable (32 combinations), while colored bars denote the weighted-average R^2 after including that variable (another 32 combinations). Values above the gray (colored)

bars indicate the R^2 before (after) including each variable, with the corresponding incremental contributions shown in parentheses above the colored bars. Error bars on the gray and colored bars indicate the 5th and 95th percentiles of the bootstrap distributions based on 10,000 resamples of years. The red dashed line represents the R^2 of the complete model (Model 64), corresponding to the sum of the contributions from all individual variables, and the red shading indicates its 5th–95th percentile bootstrap range. See Methods for details of the dominance analysis and bootstrap procedure.

References:

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Zhang, W. J. and Jiang, F.: Subseasonal Variation in the Winter ENSO–NAO Relationship and the Modulation of Tropical North Atlantic SST Variability, *Climate*, 11, 47, <https://doi.org/10.3390/cli11020047>, 2023.

Technical comments:

Line 329: Please include the affiliations of all individuals mentioned in the

Acknowledgements section.

Reply:

Thank you for your comment. We have revised the Acknowledgements section accordingly.

Reply to RC2:

This manuscript investigates the month-to-month evolution of North American spring temperature anomalies using Season-reliant EOF (S-EOF) analysis and identifies two distinct evolution modes associated with different tropical SST regimes and midlatitude circulation patterns. The study is well motivated, the methodology is appropriate, and the manuscript is clearly written. The combination of S-EOF analysis and dominance analysis provides a useful perspective on spring temperature evolution beyond seasonal-mean variability. Overall, I find the study suitable for publication after minor revision. My primary comments focus on strengthening the physical interpretation rather than questioning the main results.

Reply:

We greatly appreciate the reviewer's helpful and constructive comments. In response, we have revised the manuscript to strengthen the physical interpretation of the two S-EOF modes.

1. The manuscript argues that S-EOF1 is primarily associated with the spring NPO, whereas S-EOF2 is primarily associated with the spring NP pattern. However, the S-EOF modes describe the month-to-month evolution of North American temperature anomalies from March through May, whereas the NPO and NP are atmospheric circulation modes that themselves exhibit substantial temporal variability during spring, unlike the more slowly varying oceanic indices of ENSO and TNA SST. The manuscript demonstrates the association between seasonal-mean NPO/NP and the S-EOF modes, but it remains unclear how the month-to-month evolution of the NPO and NP gives rise to the distinct monthly pattern of S-EOF1 and S-EOF2. For example, does the monthly evolution of the NP circulation correspond to the evolving temperature pattern in S-EOF2? A clearer discussion, or additional analysis illustrating the month-to-month behavior of the associated circulation patterns, would strengthen the proposed dynamical linkage.

Reply:

Thank you for your thoughtful comment. We agree that the NPO and NP may exhibit subseasonal variations during spring. To address this issue, we have further examined the temperature and atmospheric circulation anomalies associated with the monthly NPO and NP indices (Fig. R7) and calculated the correlations of PC1 and PC2 with the monthly NPO and NP indices during spring (Table R2).

First, PC1 (PC2) is significantly correlated with the NPO (NP) index in all three spring months (Table R2). In contrast, the correlations between PC1 (PC2) and the

monthly NP (NPO) indices are much weaker. These results indicate that NPO-related (NP-related) variability during spring is preferentially associated with S-EOF1 (S-EOF2).

The temperature evolution patterns over North America associated with the **monthly** NPO (NP) indices (Fig. R7) also broadly resemble those represented by S-EOF1 (S-EOF2). The monthly NPO indices are associated with relatively persistent North Pacific SLP dipole and North American temperature anomaly patterns from March to May (Figs. R7a–c). These features are similar to the persistent temperature evolution associated with S-EOF1 (Figs. 3b–d in the manuscript). In contrast, the circulation anomalies associated with the monthly NP indices exhibit a more pronounced evolution during spring (Figs. R7d–f), with the North Pacific SLP monopole evolving from a predominantly west–east orientation in March to a northwest–southeast orientation by May, accompanied by the development of an anomalous high over the North American Arctic. Correspondingly, warm anomalies over western North America progressively retreat westward, while cold anomalies develop over central and eastern North America, particularly in April and May (Figs. R7e–f). These features closely correspond to the month-to-month evolution of temperature and circulation anomalies associated with S-EOF2 (Figs. 3f–h in the manuscript). These results are generally consistent with those based on the spring-mean NPO and NP indices (Fig. 8 in the manuscript).

Therefore, the results show a clear correspondence between the monthly NPO-related (NP-related) anomalies and the persistent (evolving) pattern represented by S-EOF1 (S-EOF2). We have added a brief discussion of these results to the revised manuscript. **Please see Lines 304–306 in the tracked-changes version of the manuscript.**

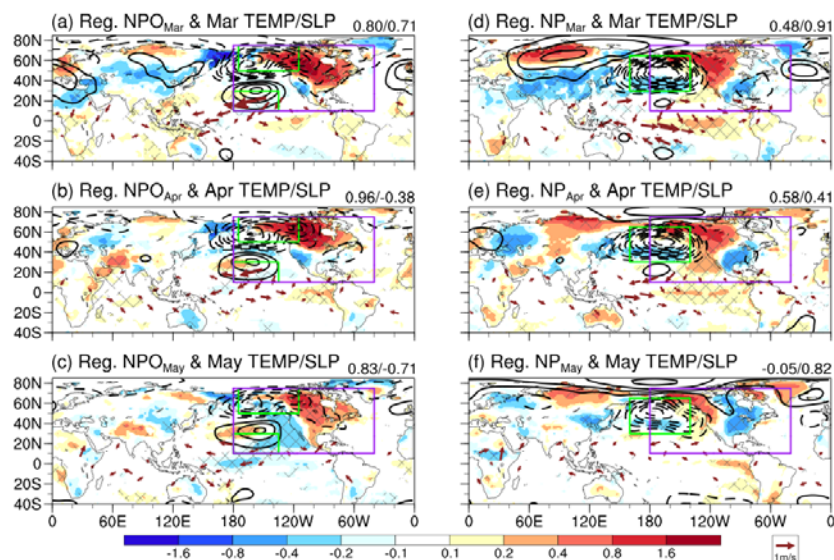


Figure R7: (a) March temperature anomalies (shading; with SST over ocean and SAT over land), SLP anomalies (black contours), and 925-hPa wind anomalies (vectors; vectors plotted only in the tropics) regressed onto the standardized March NPO index. (b, c) Same as (a), but for April and May

anomalies regressed onto the standardized April and May NPO indices, respectively. All fields are linearly detrended prior to regression. The units are °C per standard deviation of the regressed index for temperature, hPa per standard deviation of the regressed index for SLP, and m s^{-1} per standard deviation of the regressed index for 925-hPa winds. SLP contours are plotted at 0.5 hPa intervals, with the zero contour omitted. Cross-hatching indicates regions where the regressed temperature anomalies are significant at the 95% confidence level based on a two-tailed Student's *t* test. Green boxes over the North Pacific denote the key regions used to define the NPO. The purple box outlines North America. Numbers in the top-right corner of each panel indicate the pattern correlation coefficients between North American SAT anomalies regressed onto the monthly standardized NPO index and those regressed onto the standardized PC1/PC2. **(d–f)** Same as **(a–c)**, but for anomalies regressed onto the corresponding monthly standardized NP index. The green box over the North Pacific denotes the key region used to define the NP. Numbers in the top-right corner of each panel indicate the pattern correlation coefficients between North American SAT anomalies regressed onto the monthly standardized NP index and those regressed onto the standardized PC1/PC2.

Table R2 Correlation coefficients of PC1 and PC2 with the monthly NPO and NP indices during spring. All monthly indices are standardized and linearly detrended. Correlations significant at the 95% confidence level based on a two-tailed Student's *t* test are shown in bold.

	NPO (Mar)	NPO (Apr)	NPO (May)	NP (Mar)	NP (Apr)	NP (May)
PC1	0.44	0.56	0.32	0.11	0.23	0.13
PC2	0.11	-0.14	-0.32	0.36	0.41	0.42

- Throughout the manuscript, terms such as drive, govern, determine, and shape are frequently used to describe the relationships among ENSO, TNA SST, NPO/NP, and the two S-EOF modes. While the statistical analyses (S-EOF, regression, correlation, and dominance analysis) consistently demonstrate robust associations, they do not by themselves establish causality. I encourage the authors to distinguish more clearly between statistical relationships and physical causation, or to moderate the wording where appropriate. This would improve the precision of the physical interpretation without changing the main conclusions.

Reply:

Thank you for your comment. We agree that the analyses used in this study primarily establish statistical relationships and do not, by themselves, demonstrate causality. We have carefully reviewed the manuscript and revised the wording throughout to more clearly distinguish statistical relationships from physical causation.