

Research

Global multidecadal SST modes and their synchronized influence on temperature variability

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Abstract

Multidecadal climate variability is important for improving climate prediction and informing mitigation strategies. However, well-known oceanic modes such as the Pacific Decadal Oscillation (PDO) and Atlantic Multidecadal Oscillation (AMO) do not fully capture global multidecadal temperature variability, as they are limited to specific ocean basins and mixed timescales. In this study, we focus on variability at timescales longer than 50 years, where multidecadal modes dominate. Using Empirical Orthogonal Function (EOF) analysis of global sea surface temperature (SST) data, we identify two distinct large-scale modes: the Tropical Synchronized Multidecadal Oscillation (TSMO) and the High-latitude Synchronized Multidecadal Oscillation (HSMO), which explain 41.4% and 28.6% of the total variance, respectively. During the positive TSMO phase, tropical and low-latitude SST warming strengthens poleward heat transport via ocean currents and the Hadley Circulation, leading to HSMO-like warming about 11 years later. In contrast, positive HSMO phase weakens the equator-to-pole thermal gradient, resulting in negative TSMO-like tropical SST anomalies after roughly 15 years. Both TSMO and HSMO, as well as their combined signal (TSMO + HSMO), show stronger relationships with global mean land surface temperature (GMLST) than the PDO, AMO, or their combination. We propose a new global-scale climate mode—the Global Synchronized Multidecadal Oscillation (GSMO)—which integrates TSMO and HSMO and exhibits its strongest expression in the Southern Hemisphere. These findings highlight the key role of tropical and Southern Hemisphere SSTs in shaping and potentially predicting multidecadal climate variability.

Keywords: Global multidecadal variability; Ocean–atmosphere interactions; Synchronized SST oscillations; Tropical–extratropical coupling; Hadley circulation

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1. Introduction

Earth's temperature shows periodic or quasi-periodic fluctuations on multidecadal timescales, largely influenced by regional oceanic modes (Meehl et al., 2016; Xu et al., 2025; Yao et al., 2024). One of the most prominent is the Atlantic Multidecadal Oscillation (AMO), which exhibits a dominant cycle of roughly 60–80 years and has been closely linked to global temperature variability over both the instrumental period and the past millennium (Enfield et al., 2001; Mann et al., 2021; Wang et al., 2017). Positive phases of the AMO are associated with a stronger Atlantic Meridional Overturning Circulation (AMOC), which enhances poleward heat transport and leads to widespread warming across the North Atlantic and much of the Northern Hemisphere via atmospheric teleconnections (Enfield et al., 2001; Wang et al., 2024). In contrast, the global warming slowdown observed from 2000 to 2015 has been attributed largely to the Pacific Decadal Oscillation (PDO)—a North Pacific mode with dominant periodicities of about 20–30 and 50–70 years (Dai et al., 2015; Mantua and Hare, 2002). The AMO and PDO are also linked through atmospheric bridges (D'Orgeville and Peltier, 2007) on multidecadal scales, and their combined influence contributes significantly to global temperature variations (Steinman et al., 2015). Recent studies further show that AMO/PDO-related low-frequency SST variability can affect East Asian mean and extreme temperature changes (Lu and Sun, 2025; Xu et al., 2026).

Despite extensive research, uncertainties remain regarding how these oceanic modes interact and their relative contributions to global climate variability (Fang et al., 2019; Power et al., 2021; Wu et al., 2025; Xu et al., 2025). These interactions have been linked to atmospheric bridges, oceanic memory, and cross-basin ocean–atmosphere coupling (D'Orgeville and Peltier, 2007; Xu et al., 2025). Most existing studies identify these modes from sea surface temperature (SST) data that span a wide range of timescales and focus on individual ocean basins (Enfield et al., 2001; Henley et al., 2015; Mantua and Hare, 2002). As a result, potential global-scale oceanic modes operating specifically on multidecadal timescales remain underexplored.

In this study, we address this knowledge gap by filtering out higher-frequency SST variability to isolate and analyze distinct multidecadal global oceanic modes. We further examine their dominant influence on global climate. Our results highlight important mechanisms by which synchronized multidecadal SST variability in both tropical and high-latitude regions drive global temperature changes, offering new insights into the dynamics of multidecadal climate variability.

2. Materials and methods

2.1. Climate data

Multidecadal oceanic modes were identified using the Hadley Centre Sea Ice and Sea Surface Temperature dataset (HadISST), which provides monthly SST fields on a $1^\circ \times 1^\circ$ grid from 1870 to 2024 (Rayner et al., 2003). Atmospheric circulation variables, including zonal and meridional winds, geopotential height (GPH) at 1000 hPa and 200 hPa, and the meridional mass stream function (MSF), were obtained from NOAA's Twentieth Century Reanalysis version 3 (20CRv3) for 1806–2015. The 20CRv3 dataset is provided on a $1^\circ \times 1^\circ$ grid (Compo et al., 2011; Slivinski et al., 2019). It provides dynamically consistent, long-term atmospheric fields suitable for investigating circulation patterns associated with the identified oceanic modes. To assess the robustness of the identified multidecadal SST modes, we further applied the same 50-year low-pass EOF analysis to two additional long-term SST datasets: ERSSTv5 from NOAA (1854–2024, $2^\circ \times 2^\circ$; Huang et al., 2017) and COBE-SST2 from JMA (1850–2024, $1^\circ \times 1^\circ$; Hirahara et al., 2014). These datasets provide temporal coverage broadly comparable to that of HadISST (1870–2024, $1^\circ \times 1^\circ$), allowing an inter-dataset comparison of the leading multidecadal modes.

To assess how these oceanic modes modulate land surface air temperature, we used monthly air temperature data from the Climate Research Unit Time Series version 4.09 (CRU TS4.09) dataset, provided on a $0.5^\circ \times 0.5^\circ$ grid and covering the period 1901–2024 (Harris et al., 2020). Global monthly mean land surface temperatures were calculated as area-weighted averages over all grid cells in the CRU TS4.09 dataset. The AMO index, obtained from NOAA/NCEI, was defined as detrended area-averaged SST anomalies over the North Atlantic (Enfield et al., 2001). The PDO index, also from NOAA/NCEI, was derived by projecting North Pacific SST anomalies onto the Mantua PDO regression pattern (Mantua and Hare, 2002).

2.2. Analysis

Empirical Orthogonal Function (EOF) analysis (Lorenz, 1956) was used to extract the dominant spatial patterns of SST variability and their corresponding PC time series. In the global SST EOF analysis, area weighting was applied using the square root of cosine latitude to account for grid-area differences across latitudes. The separability of the leading EOF modes was assessed using the North test, and the first and second EOF modes passed the test in all EOF analyses presented in this study. Low-pass filtering was performed in the frequency domain using

the Fast Fourier Transform (FFT), following standard procedures for spectral decomposition and smoothing of climatic time series (Bloomfield, 2004). All data used in the analyses were first smoothed with a 50-year low-pass filter and then linearly detrended prior to analysis. Statistical significance is assessed using a two-tailed Student's *t*-test based on an effective sample size that accounts for autocorrelation, following the method (Quenouille, 1952).

The zonal mean MSF was calculated from the 20CRv3 meridional wind fields. At each pressure level, the MSF was obtained by vertically integrating the zonal-mean meridional wind, weighted by surface pressure and latitude (Hu and Fu, 2007; Oort and Yienger, 1996).

3. Results

3.1. Dominant multidecadal global SST modes

To isolate multidecadal SST variability, we applied Empirical Orthogonal Function (EOF) analysis to low-pass-filtered global SST data. The dominant modes of multidecadal variability emerged clearly through a sharp increase in variance explained by the leading EOF components. By testing a range of cutoff periods, we identified a peak in the variance explained by the first two EOFs—EOF1 and EOF2—at a 50-year timescale (Fig. 1a),

indicating the presence of coherent global multidecadal modes.

At this 50-year filtering threshold, EOF1 and EOF2 explain 41.4% and 28.6% of the total variance, respectively. Among the two, the second principal component (PC2) shows particularly strong multidecadal periodicity (Fig. 1b). Spatially, EOF1 features positive loadings across the tropical and low-latitude regions—including the western Pacific, Indian Ocean, and eastern Pacific—and negative loadings at high latitudes, particularly in the north-central Pacific and the North Atlantic in a horseshoe-shaped pattern (Fig. 1c). We referred to this pattern as the Tropical Synchronized Multidecadal Oscillation (TSMO). A positive TSMO phase corresponds to anomalous warming in the tropical and low-latitude oceans and cooling in parts of the high-latitude North Pacific and North Atlantic. In contrast, EOF2 displays strong positive loadings in high-latitude regions, especially near the Gulf of St. Lawrence, the East China Sea, and the Scotia Sea (Fig. 1d). We defined this mode as the High-latitude Synchronized Multidecadal Oscillation (HSMO). A positive HSMO phase corresponds to anomalous warming in these key high-latitude regions. These spatial patterns remain consistent across different seasons (Figs. A1–A4), underscoring their robustness. The identified multidecadal SST modes are robust across datasets. In ERSSTv5

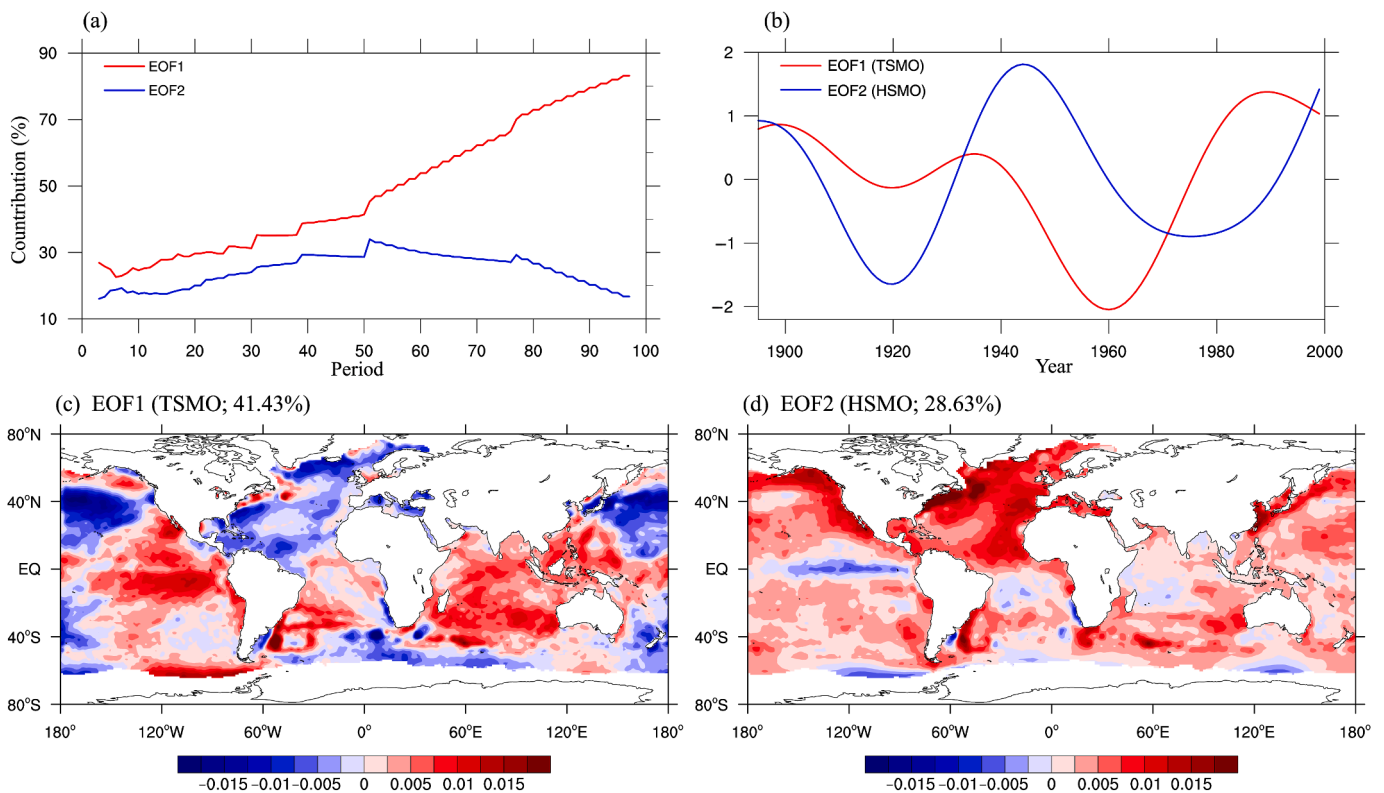


Fig. 1. Spatiotemporal patterns of the leading multidecadal modes in global annual mean sea surface temperature (SST), (a) variance explained by the first two Empirical Orthogonal Functions (EOF1 and EOF2) at different timescales, based on low-pass filtered SST, (b) corresponding principal component time series, and (c, d) spatial patterns of EOF1 and EOF2 derived from SST filtered with a 50-year low-pass filter (Linear trends were removed before analysis. Analyses use HadISST data from 1870 to 2024 to avoid edge effects from filtering, EOF calculations are based on data from 1895 to 1999).

(Fig. A5), EOF1 and EOF2 are broadly consistent with HadISST EOF1 and EOF2 in both spatial pattern and temporal evolution. In COBE-SST2 (Fig. A6), the same two physical modes are also recovered, although their order is reversed. Overall, these results support the robustness of the identified TSMO and HSMO across independent SST products.

To assess the physical relevance of these modes, we compared them with regional mean SSTs. The TSMO shows a strong correlation with annual mean SST in the low-latitude band (30°S–20°N; $r = 0.77$, $p < 0.01$), while the HSMO is even more strongly correlated with SSTs in high-latitude regions, including the Gulf of St. Lawrence, North Atlantic (30°N–60°N, 80°W–40°W), East China Sea (20°N–45°N, 115°E–130°E), and Scotia Sea (50°S–20°S, 57°W–45°W) ($r = 0.89$, $p < 0.01$; Fig. 2a–c). These results confirm that the low-latitude SST region represents the main SST signature of EOF1/TSMO, whereas the three extratropical loading regions represent the main SST signature of EOF2/HSMO.

The TSMO and HSMO are temporally linked: when the TSMO leads the HSMO by ~ 11 years, they exhibit a significant positive correlation ($r = 0.32$, $p < 0.01$); when the HSMO leads the TSMO by ~ 15 years, the correlation becomes strongly negative ($r = -0.83$, $p < 0.01$; Fig. 2d).

These results suggest a recurring phase relationship and potential coupling between tropical and high-latitude multidecadal SST variability.

3.2. Dynamics and interactions of the TSMO and HSMO

The TSMO is associated with significant positive correlations with GPH anomalies across low-to mid-latitudes at both 1000 hPa (Fig. 3a) and 200 hPa (Fig. 3b), especially over the Atlantic and western-central Pacific. At the same time, negative GPH anomalies appear over polar regions, indicating a barotropic atmospheric response. This pattern reflects enhanced tropospheric temperatures and increased atmospheric thickness in the tropics, contrasted by cooling over higher latitudes. The resulting meridional SST gradient strengthens, modulating large-scale circulation and stationary wave activity, particularly over the Atlantic–Pacific sector.

The HSMO primarily influences high-latitude atmospheric variability. During the positive HSMO phase, at 1000 hPa, the GPH anomalies exhibit a seesaw pattern, with positive anomalies over the poles and negative anomalies over mid-latitudes (Fig. 3c). At 200 hPa, positive GPH response extend across the extratropics. In the sub-

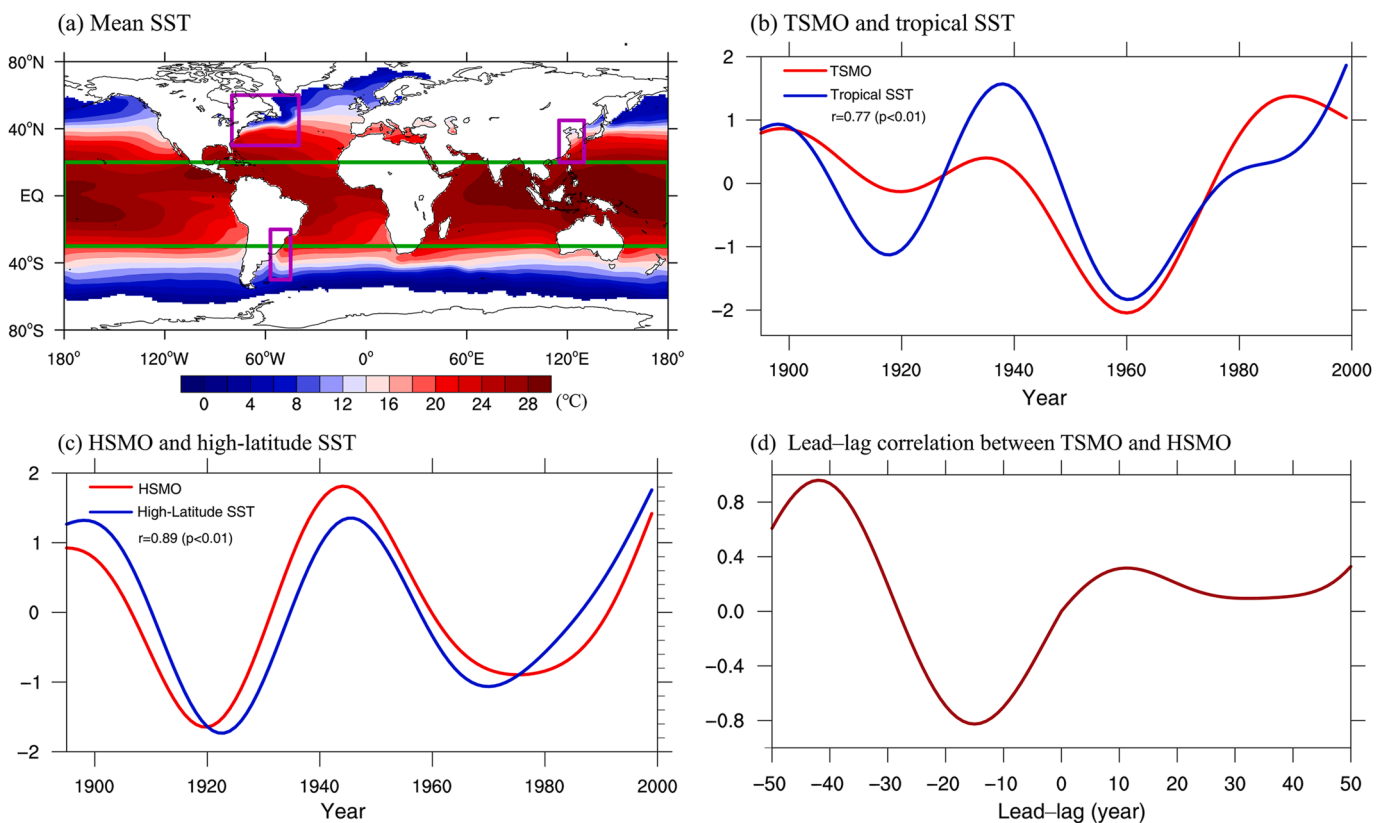


Fig. 2. Spatial domains and relationships between multidecadal sea surface temperature (SST) modes and regional SST anomalies, (a) climatological mean SST across global oceans, (The green box outlines the tropical domain (30°S–20°N) used in (b), while purple boxes highlight high-latitude regions (30°–60°N, 80°–40°W), (20°–45°N, 115°–130°E), and (50°–20°S, 57°–45°W) used in (c)), (b) time series of the Tropical Synchronized Multidecadal Oscillation (TSMO) compared with tropical SST anomalies, (c) time series of the High-latitude Synchronized Multidecadal Oscillation (HSMO) compared with high-latitude SST anomalies, and (d) lead-lag correlation between TSMO and HSMO indices.

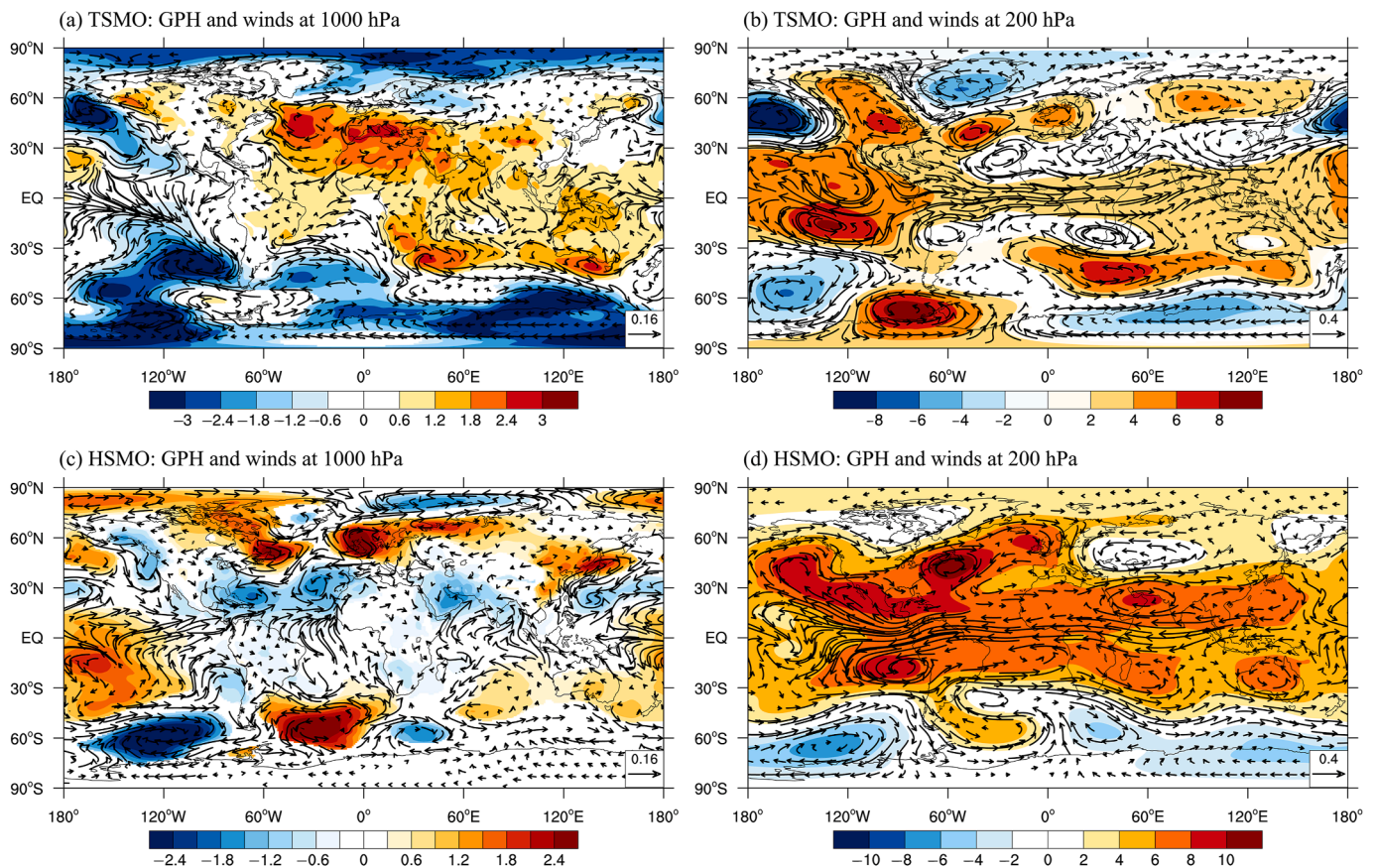


Fig. 3. Regression patterns of global sea surface temperature (SST) Empirical Orthogonal Function (EOF) modes with geopotential height (GPH) and wind fields for 1895–1999. Panels show regressions of GPH and horizontal wind vectors (m/s) at 1000 hPa (a, c) and 200 hPa (b, d) onto the standardized principal components of EOF1 (a, b) and EOF2 (c, d) (Shading and vectors indicate values statistically significant at the 95% confidence level).

tropics, the anomaly field shows a vertically contrasted structure, with negative anomalies at low levels and positive anomalies aloft. This structure likely reflects thermal wind adjustments caused by high-latitude warming and a weakened meridional temperature gradient, corresponding to weakened background atmospheric baroclinicity and thus reduced baroclinic instability. These changes influence mid-latitude westerlies and upper-tropospheric wave activity. Consistent with this mechanism, the seesaw GPH pattern is associated with weakened subpolar westerlies and easterly wind anomalies (Fig. 3c and d), indicating that high-latitude warming during the positive HSMO phase reduces the equator-to-pole thermal gradient, thus weakening the westerlies (Bridges et al., 2023; Xu et al., 2024). The reduced westerly winds contribute to surface warming in the Gulf of St. Lawrence, East China Sea, and Scotia Sea by suppressing the upward mixing of cold subsurface water, consistent with the positive HSMO SST pattern.

The TSMO and HSMO are dynamically connected through large-scale thermal exchanges. During TSMO-positive phases, low-latitude warming—especially stronger in the Southern Hemisphere (SH)—drives enhanced atmospheric meridional heat transport both from the SH to the Northern Hemisphere (NH) and from the NH tropics toward high latitudes. This is facilitated by a

stronger and southward-shifted NH Hadley cell, as indicated by the enhanced positive meridional mass stream function over 20°S–10°N (Fig. 4a). The southward shift of the ascending branch aligns with regions of increased net energy convergence, intensifying poleward energy flux through upper-level divergence and latent heat release (Bordoni and Schneider, 2008; Held and Schneider, 1999; Lindzen and Hou, 1988).

The TSMO also influences surface winds, with enhanced westerlies at mid-to-high latitudes and easterly anomalies in the tropics. These patterns coincide with anticyclonic circulation anomalies over the North Atlantic, Eurasia, and the mid-latitude North Pacific (30°N–40°N; Fig. 3a). The resulting surface zonal wind shear between tropical and higher latitudes generates large-scale negative wind curl anomalies (Fig. 4c), which induce southward Sverdrup transport within the Atlantic and Pacific interiors. To conserve mass, the western boundary currents (i.e., the Gulf Stream and Kuroshio) intensify, acting as primary conduits for poleward oceanic heat transport (Kwon et al., 2010; Wunsch, 2005).

In contrast, HSMO-related high-latitude warming coincides with a reconfiguration of the Hadley circulation: the NH cell weakens while the SH cell strengthens, promoting equatorward heat transport. Surface wind anoma-

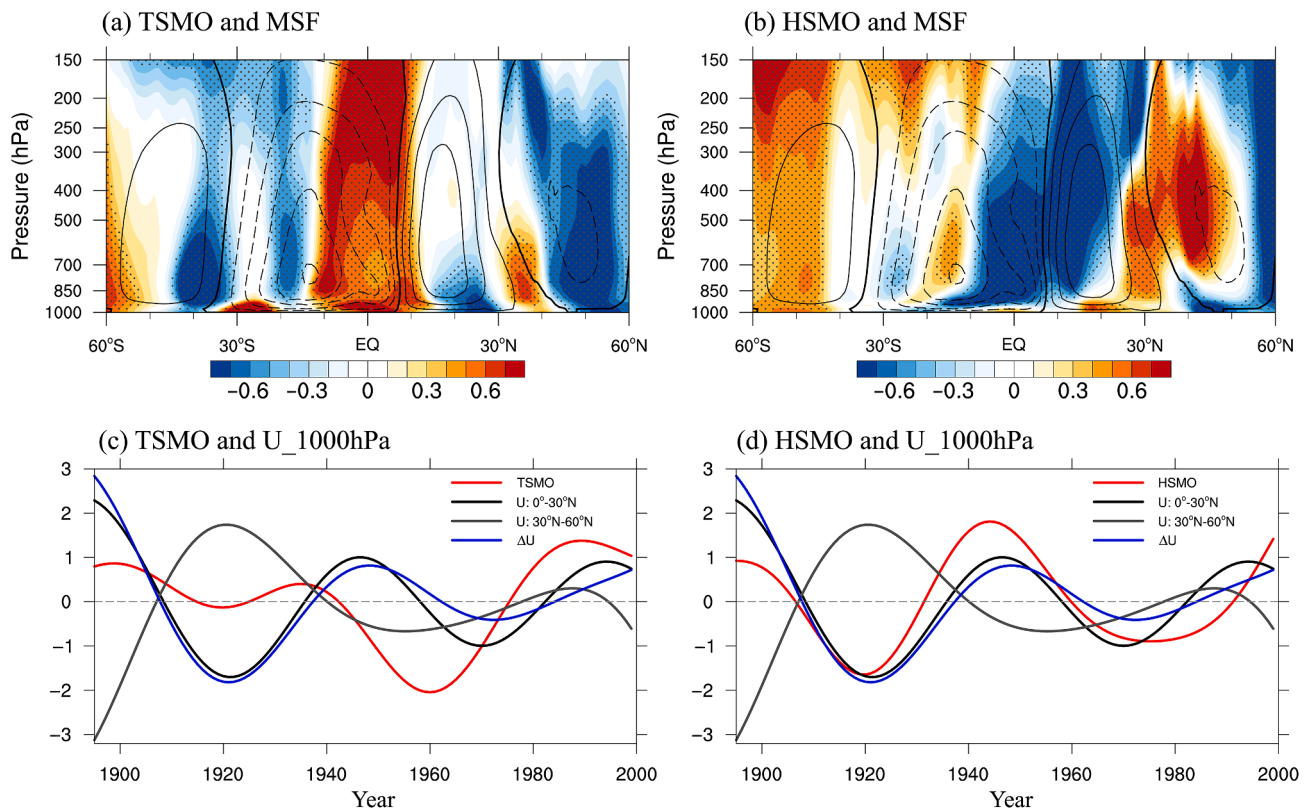


Fig. 4. Relationship between leading sea surface temperature (SST) modes and the zonal mean meridional mass stream function (MSF), the first (a; Tropical Synchronized Multidecadal Oscillation, TSMO) and second (b; High-latitude Synchronized Multidecadal Oscillation, HSMO) Empirical Orthogonal Function (EOF) modes (Contours depict the climatological MSF, with solid (dashed) lines indicating clockwise (anticlockwise) circulation, corresponding to the Hadley cells in each hemisphere), (c) and (d) temporal variations of the TSMO and HSMO indices (red) alongside 1000 hPa zonal wind anomalies averaged over 0° – 30° N and 30° N– 60° N (The meridional wind shear ΔU ($U_{30^{\circ}\text{N}-60^{\circ}\text{N}} - U_{0^{\circ}-30^{\circ}\text{N}}$) influences Sverdrup transport and modulates meridional ocean heat redistribution. Stippling marks areas where correlations are significant at the 95% confidence level).

lies associated with the HSMO show cyclonic shear between tropical and mid-latitude zones, particularly evident in anticyclonic circulations near 30° N– 40° N. A statistically significant relationship between the HSMO index and zonal wind shear (Fig. 4d) suggests that this configuration promotes anomalous southward Sverdrup transport and weakened western boundary currents, leading to enhanced equatorward redistribution of oceanic heat.

Together, during the positive TSMO phase, the TSMO reflects tropical warming and intensified poleward energy transport, while during the positive HSMO phase, the HSMO embodies high-latitude warming and a weakened equator-to-pole thermal gradient. Their lead–lag relationship (Fig. 2d) implies a coherent multidecadal thermal exchange cycle: positive TSMO-induced poleward heat transport likely contributes to positive HSMO-like high-latitude warming roughly 11 years later (Fig. 4a and c), while positive HSMO-related warming is followed by a transition toward negative TSMO-like tropical SST anomalies about 15 years later (Fig. 4b and d). This dynamic interplay underscores the coupled nature of tropical and high-latitude processes in driving multidecadal SST variability. The corresponding mechanism for the negative phase are broadly symmetric, with opposite signs, and are therefore not shown for brevity.

3.3. TSMO and HSMO on global temperature

The TSMO shows strong positive correlations with GMLST across most land areas, with only a few regions—such as eastern Canada, Greenland, and southeastern South America—exhibiting weak or negative correlations (Fig. 5a). Similarly, the HSMO is positively correlated with GMLST over wide areas but features negative correlations in parts of central Asia, Australia, and certain regions of Africa and South America (Fig. 5b).

To capture the combined effect of tropical and high-latitude multidecadal variability, we defined the Global Synchronized Multidecadal Oscillation (GSMO) as the sum of the standardized TSMO and HSMO series. This combined mode exhibits significantly stronger correlations with GMLST than either TSMO or HSMO alone. In particular, regions such as Alaska, northern Canada, and Siberia show correlation coefficients exceeding 0.90 with GSMO (Fig. 5c), underscoring its dominant influence on surface temperature in high-latitude regions.

When compared with traditional oceanic modes—PDO and AMO—our identified modes demonstrate stronger links with GMLST (Fig. 6). The TSMO correlates more strongly with GMLST ($r = 0.63$, $p < 0.01$) than PDO ($r = 0.52$, $p < 0.01$), and the HSMO shows a higher cor-

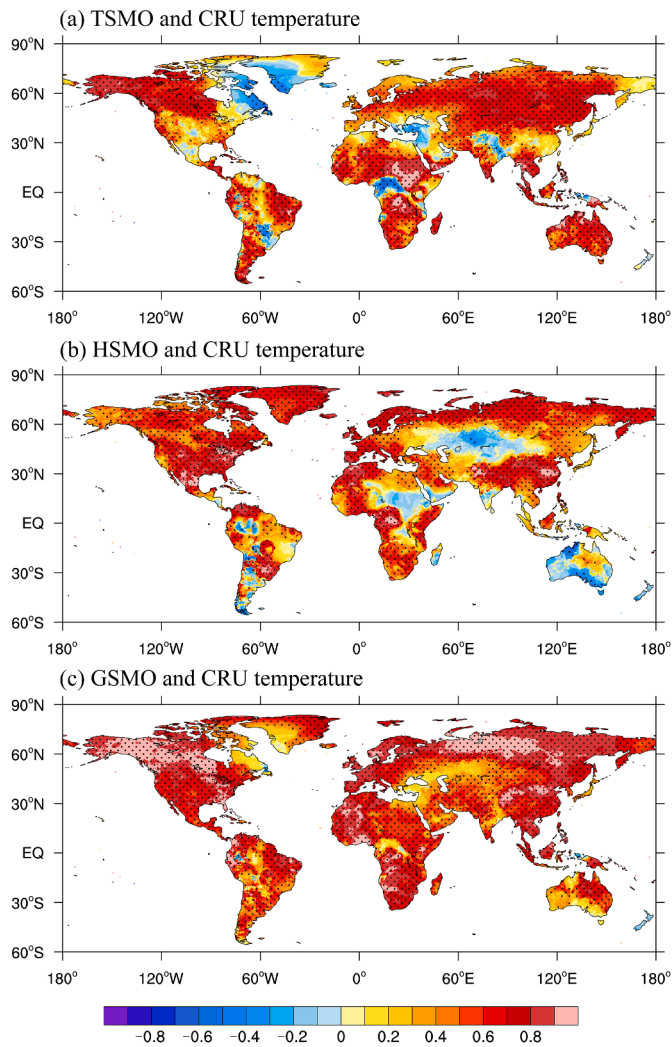


Fig. 5. Correlations between global land surface temperature and (a) the first SST mode (EOF1; Tropical Synchronized Multidecadal Oscillation, TSMO), (b) the second SST mode (EOF2; High-latitude Synchronized Multidecadal Oscillation, HSMO), and (c) their combined mode (TSMO + HSMO; Global Synchronized Multidecadal Oscillation, GSMO) for 1901–1999 (All data were smoothed with a 50-year low-pass filter and then linearly detrended prior to analysis. Stippling marks correlations significant at the 95% confidence level).

relation ($r = 0.55$, $p < 0.01$) than AMO ($r = 0.28$, $p < 0.1$). Notably, the GSMO exhibits the highest correlation with GMLST ($r = 0.86$, $p < 0.01$), surpassing even the combined influence of PDO and AMO ($r = 0.56$, $p < 0.01$).

These results emphasize the critical role of synchronized multidecadal SST variability—captured by the TSMO and HSMO—in shaping global surface temperature patterns, and suggest that GSMO may serve as a more robust indicator of multidecadal climate variability than conventional modes.

This stronger relationship likely reflects the combined influence of low- and high-latitude SST anomalies on large-scale atmosphere–ocean coupling. Tropical SST variability may affect land temperatures through broad circulation adjustments, whereas high-latitude SST variability may

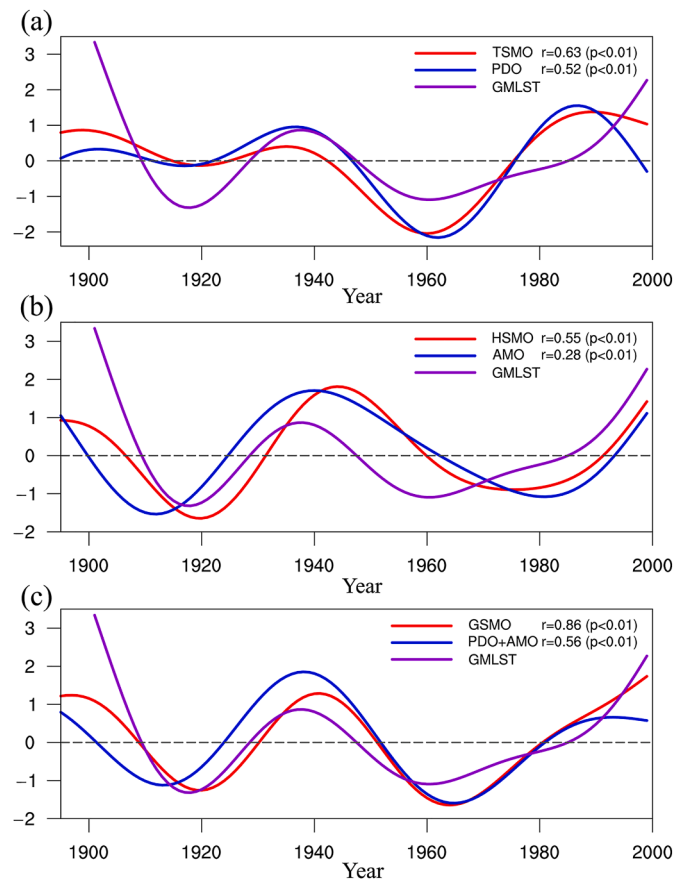


Fig. 6. Influence of multidecadal oceanic modes on global mean land surface temperature (GMLST), (a) comparison of the Tropical Synchronized Multidecadal Oscillation (TSMO), Pacific Decadal Oscillation (PDO), and GMLST, with their corresponding correlation coefficients, (b) comparison of the High-latitude Synchronized Multidecadal Oscillation (HSMO), Atlantic Multidecadal Oscillation (AMO), and GMLST, including their correlations, and (c) comparison of the Global Synchronized Multidecadal Oscillation (GSMO, defined as the sum of the standardized TSMO and HSMO series), the combined PDO + AMO (defined as the sum of the standardized PDO and AMO series), and GMLST.

contribute through meridional heat redistribution. This helps explain why GSMO shows a closer linkage to GMLST than the individual modes alone.

4. Discussion

Our proposed TSMO and HSMO exhibit stronger modulation of global multidecadal temperature variability than traditional modes, as they are derived from a global framework and specifically isolate variability on multidecadal timescales. The TSMO shares spatial features with the PDO (Mantua and Hare, 2002) in the North Pacific but also shows strong loadings across low-latitude regions, especially the tropical Pacific and Indian Oceans. It resembles the spatial pattern of the Interdecadal Pacific Oscillation (IPO) (Henley et al., 2015), though with enhanced signals over the western Pacific and Indian Oceans. Among existing modes, the TSMO most closely

resembles the PDO, but with more prominent loadings in the tropical eastern Pacific and Indian Oceans (Fang et al., 2018), regions known to strongly influence monsoon variability on multidecadal timescales (Fang et al., 2024). While the tropical and subtropical Pacific dominate inter-annual climate variability (Timmermann et al., 2018), they also play a key role in shaping multidecadal variability (Levine et al., 2017; Power et al., 2021; Sun et al., 2017), including during the recent warming hiatus (Kosaka and Xie, 2013; Power et al., 2021). Tropical SST anomalies affect multidecadal climate primarily by altering large-scale atmospheric circulation—through shifts in the Walker and Hadley cells—and by generating stationary Rossby waves that redistribute heat and precipitation on a global scale (Meehl et al., 2016; Power et al., 2021; Wang et al., 2013). These results support the central role of tropical SSTs in driving global multidecadal thermal variability.

The HSMO shows some resemblance to the AMO (Enfield et al., 2001; Schlesinger and Ramankutty, 1994), but with key differences. Unlike the AMO, which features strong loadings across the broader North Atlantic, the HSMO centers around the Gulf of St. Lawrence and extends into other high-latitude regions, including the East China Sea and Scotia Sea. These loading centers are located in mid-latitudes dominated by strong westerly winds. The pronounced HSMO signals in these zones likely reflect enhanced atmosphere–ocean coupling along storm tracks and frontal zones, where sharp gradients in temperature promote intense air–sea interaction (Frankignoul et al., 1997; Kwon et al., 2010; Qiu et al., 2007). Dynamically active regions such as the Gulf Stream extension and Kuroshio–Oyashio confluence exhibit strong baroclinic instability and mesoscale eddy activity, both of which sustain low-frequency SST variability (Kwon and Deser, 2007; Taguchi et al., 2007). The alignment of HSMO loadings with these features suggests that interactions among storm-track activity, oceanic processes, and atmospheric feedbacks amplify its spectral coherence and distinguish it from the AMO.

The combined influence of low-latitude (TSMO) and high-latitude (HSMO) patterns results in a global mode—GSMO—that displays widespread positive SST correlations, especially in the Southern Hemisphere. Here, both TSMO and HSMO contribute positive loadings, notably in the western Pacific, Indian Ocean, and southern Pacific. In contrast, the Northern Hemisphere features weaker GSMO loadings due to partial cancellation between the TSMO and HSMO, except in areas like the Gulf of St. Lawrence and East China Sea, where their contributions align. Negative SST correlations over the north-central Pacific (Fig. 7a) mainly reflect the negative loadings from the TSMO. The GSMO's associated atmospheric circulation anomalies resemble those of the TSMO more than the HSMO, notably in showing high-pressure anomalies over the North Atlantic and southern Australia (Fig. 7b and c). The more pronounced Southern Hemisphere signature of

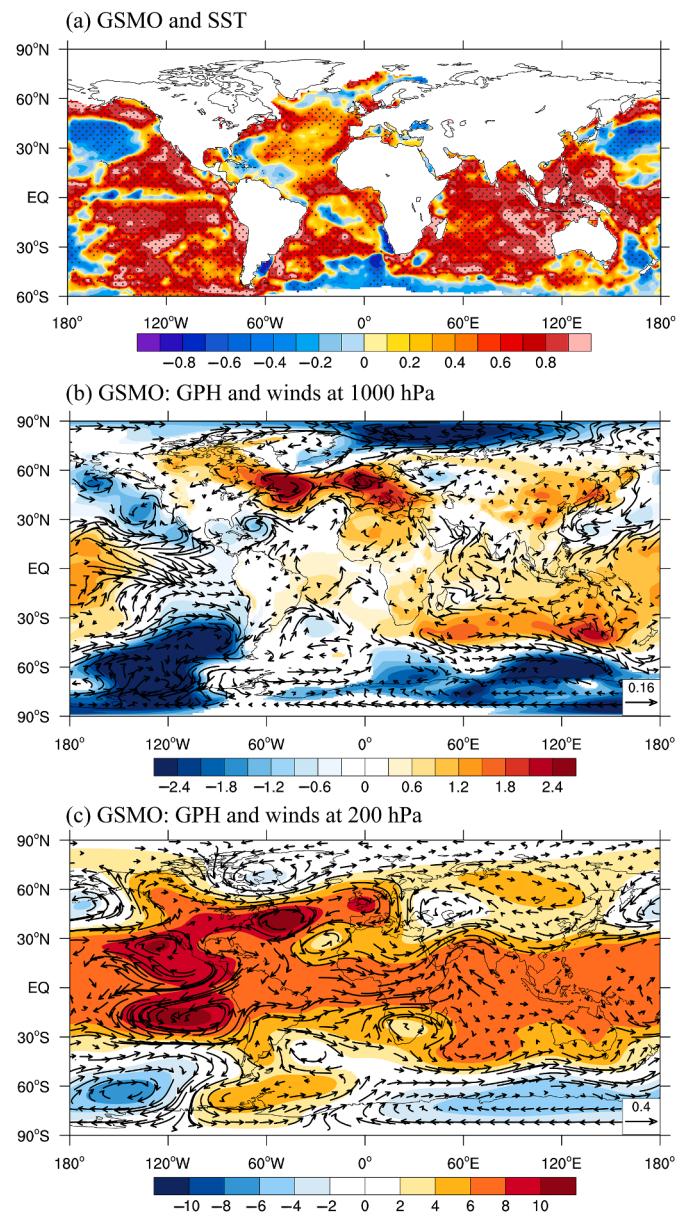


Fig. 7. Oceanic and atmospheric patterns linked to the Global Synchronized Multidecadal Oscillation (GSMO), (a) correlation between GSMO and global sea surface temperature (SST) for 1901–1999, regression of geopotential height (GPH) and wind vectors (m/s) at 1000 hPa (b) and 200 hPa (c) onto the GSMO index for 1895–1999 (Stippling in (a) marks correlations significant at the 95% confidence level. In (b) and (c), only regression values significant at the 95% level are shown for both shading and vectors).

the GSMO may reflect the fact that PDO and AMO are basin-specific Northern Hemisphere modes, whereas GSMO is derived from the global SST field. In addition, the larger and more zonally continuous ocean area of the Southern Hemisphere may favor broader inter-basin coherence on multidecadal timescales.

Although GSMO-related SST anomalies extend across most ocean basins, the associated atmospheric responses are particularly strong over mid-latitude regions characterized by strong westerlies and baroclinicity, such as the

North Atlantic and southern Australia. These areas are key sites for jet–wave interactions and the formation of Rossby wave trains (Branstator, 2002; Trenberth and Hurrell, 1994), which can transmit energy and momentum across hemispheres. This suggests that regional air–sea coupling in such dynamically sensitive zones can exert disproportionate influence on global atmospheric circulation and surface air temperature patterns (Hoskins and Karoly, 1981). Moreover, the globally consistent SST anomalies of the GSMO may reflect responses to external radiative forcings, particularly solar variability and volcanic forcing, as well as oceanic adjustments associated with variations in the thermohaline circulation. These processes may help synchronize SST variability across ocean basins (Knight et al., 2005; Schneider and Bordon, 2008; Stenchikov et al., 2006; Swingedouw et al., 2015).

To further assess the role of external forcing, we compared the time series of TSMO and HSMO with major external forcing factors, including total solar irradiance and volcanic forcing (Fig. A7). The results show that TSMO exhibits a moderate correlation with total solar irradiance, indicating that solar forcing may play a role in modulating tropical multidecadal variability. In contrast, the timing of strong volcanic forcing does not correspond well to the peaks and troughs of either TSMO or HSMO, suggesting that volcanic forcing is unlikely to be the dominant driver of these modes. Therefore, although external forcing may contribute to or modulate large-scale temperature variability on multidecadal timescales, the TSMO and HSMO cannot be explained solely as a common forced response. Instead, both modes are more likely dominated by internal variability, with external forcing playing a secondary role. The relatively closer relationship between TSMO and external forcing, together with the weaker forcing signal in HSMO, may help explain the asymmetric lead–lag relationship between the two modes (Fig. 2d). HSMO, primarily associated with internal low-frequency variability, can be viewed as a slowly varying large-scale background state that modulates tropical variability, leading to a clearer response in TSMO when HSMO leads. In contrast, TSMO mainly represents tropical variability and cannot fully capture the broader hemispheric-scale variability in HSMO, resulting in a much weaker lead–lag relationship when TSMO leads.

Some limitations should also be noted. Uncertainties in early SST data, the finite length of the available records, and dataset-dependent differences may affect the extraction of long-period modes. In addition, our results suggest possible roles of wind-driven ocean circulation and meridional heat redistribution, while the contributions of slow oceanic processes warrant further investigation. Ocean heat storage, gyre adjustment, western boundary-current variability, and AMOC variability may provide important memory for multidecadal SST variability. Future analyses using longer and higher-quality datasets, ocean heat-budget diagnostics, ocean reanalyses, and coupled-model experiments will help

further assess the robustness of the identified modes and better quantify these oceanic contributions.

5. Conclusions

A global SST mode that dominates multidecadal climate variability was identified in this study. We found that coherent multidecadal oceanic variability emerges at timescales longer than 50 years, with peak co-variability at that threshold. EOF1 (TSMO) captures synchronized warming in the tropical oceans, which enhances poleward heat transport via wind-driven ocean currents and expansion of the Hadley cell. This process contributes to high-latitude warming represented by EOF2 (HSMO), explaining the observed strong positive correlation when TSMO leads HSMO by around 11 years. In contrast, warming in the HSMO suppresses poleward heat transport and can lead to tropical cooling, consistent with the strong negative correlation when HSMO leads by about 15 years. The combined effect of the TSMO and HSMO—captured by the GSMO—modulates global mean land surface temperature more effectively than the AMO, PDO, or their combination. Together, the TSMO and HSMO represent a coupled feedback system underlying GSMO variability. These findings underscore the importance of adopting a global perspective to better understand multidecadal climate variability and its links to both internal feedbacks and external forcings.

Declaration of competing interest

The authors declare no conflict of interest.

CRedit authorship contribution statement

Ke-Yan Fang: Writing – review & editing, Writing – original draft, Visualization, Conceptualization. **Xiao-Xun Xie:** Writing – review & editing, Writing – original draft, Visualization, Methodology. **Shu-Heng Lin:** Writing – review & editing, Writing – original draft, Visualization, Methodology. **Hao Wu:** Writing – review & editing. **Jane Liu:** Writing – review & editing, Conceptualization. **Jin-Bao Li:** Writing – review & editing. **Cesar Azorinmolina:** Writing – review & editing. **Tinghai Ou:** Writing – review & editing. **Wan-Ru Tang:** Writing – review & editing. **Deliang Chen:** Writing – review & editing, Conceptualization.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.accre.2026.05.020>.

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