

Interdecadal winter temperature variability driven by the East China Sea Mode: A global perspective

Keyan FANG^{1*}, Hao WU^{1,2}, Shuheng LIN¹, Jun CHENG³, Jane LIU^{1,4}, Deliang CHEN⁶, Jinbao LI⁷, Cesar AZORIN-MOLINA⁸, Zheng ZHAO¹, Frode STORDAL⁹, Shuo HAO¹¹, Nicole DAVI^{12,10}, Tinghai OU⁵, Hang XING¹ & Fahu CHEN¹⁰

¹ Fujian Institute for Cross-Straits Integrated Development, Key Laboratory of Humid Subtropical Eco-geographical Process (Ministry of Education), College of Geographical Sciences, Fujian Normal University, Fuzhou 350007, China

² Jiangxi Provincial Key Laboratory of Genesis and Remediation of Groundwater Pollution, School of Water Resources and Environmental Engineering, East China University of Technology, Nanchang 330013, China

³ School of Marine Sciences, Nanjing University of Information Science and Technology, Nanjing 210044, China

⁴ Department of Geography and Planning, University of Toronto, Toronto M5S 3G3, Canada

⁵ Regional Climate Group, Department of Earth Sciences, University of Gothenburg, Gothenburg 460, Sweden

⁶ Department of Earth System Sciences, Tsinghua University, Beijing 100084, China

⁷ Department of Geography, The University of Hong Kong, Hong Kong 999077, China

⁸ Centro de Investigaciones sobre Desertificación, Consejo Superior de Investigaciones Científicas (CIDE, CSIC-UV-Generalitat Valenciana), Climate, Atmosphere and Ocean Laboratory (Climatoc-Lab), Moncada, Valencia 46113, Spain

⁹ Department of Geosciences, University of Oslo, Oslo 0316, Norway

¹⁰ Alpine Paleocology and Human Adaptation Group (ALPHA), Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100101, China

¹¹ Tree Ring Laboratory, Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY 10964, USA.

¹² Department of Environmental Science, William Paterson University, Wayne, NJ 07470, USA

* Corresponding author (email: kfang@fjnu.edu.cn)

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Abstract Global winter temperatures show pronounced interdecadal variability compared to other seasons, yet the main modulators at a global scale remain unclear. We strengthened the signal of interdecadal winter temperature variability by eliminating the high-frequency signal driven by the El Niño–Southern Oscillation (ENSO). Our analysis, using observations and simulations, identifies Sea Surface Temperature (SST) variability in the East China Sea as a key driver of global interdecadal winter temperature anomalies. We introduce the East China Sea Mode (ECSM), a winter-specific mode that significantly influences global winter temperatures. The East China Sea, adjacent to the East Asian Winter Monsoon (EAWM) area, is a critical region impacted by this monsoon system. The ECSM induces global winter temperature anomalies by modulating the dominant interdecadal atmospheric teleconnections, positioned within a crucial area of the teleconnection wave train. Notably, the influence of the ECSM extends beyond the typical range of influence of the Pacific Decadal Oscillation (PDO), with the combined effects of ECSM and PDO shaping temperature patterns across Eurasia, North America, and parts of the Southern Hemisphere. This study highlights the critical role of SSTs in the East China Sea in affecting winter temperature variability, which complements the traditional focus on the eastern part as represented by the PDO.

Keywords Winter temperature, Winter monsoon, El Niño–Southern Oscillation, East China Sea, East China Sea Mode

1. Introduction

Global warming driven by anthropogenic greenhouse gases is most prominent during boreal winter (IPCC, 2021; Armstrong McKay et al. 2022), yet persistent interdecadal to multidecadal (10–60 yr) winter cooling is observed in specific regions, such as central Eurasia (Blackport et al., 2019; Cohen et al., 2020; Smith et al., 2022). Some studies suggested that the amplified Arctic warming and associated sea ice loss could weaken the mid-latitude westerlies, leading to winter cooling (Mori et al., 2014). However, causal relationships of these associations were questioned in some modeling studies (McCusker et al., 2016; Blackport et al., 2019; Cohen et al., 2020). The occurrence of winter cooling between 1995 and 2013 highlights the need to study the interdecadal to multidecadal (10–60 yr) variability of

winter temperatures on a global scale (He et al., 2020; Yin et al., 2023).

Global temperatures show distinct interdecadal fluctuations, such as the warming slowdown observed during 1940–1975 and 1998–2012 over the past century (Kosaka and Xie, 2013; Dai et al., 2015; Medhaug et al., 2017). The dominant modes of Atlantic and Pacific Sea Surface Temperature (SST) variability, including the Atlantic Multidecadal Oscillation (AMO) (Enfield et al., 2001) and the Pacific Decadal Oscillation (PDO) (Mantua and Hare 2002) or Interdecadal Pacific Oscillation (IPO) (Henley et al., 2015), are widely recognized as key drivers of global temperature on interdecadal timescales (Dai et al., 2015; Steinman et al., 2015; Wang et al., 2017; Fang et al., 2018; Mann et al., 2021). However, the influence of specific sub-basin SST anomalies, especially in the western North Pacific and its

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marginal seas, on global interdecadal winter temperature variability has received comparatively less attention. Moreover, the East Asian winter climate is strongly influenced by both the East Asian winter monsoon, ENSO, and their associated air-sea interactions over the Asian region (Wang et al., 2000; Kim et al., 2017; Lin et al., 2024). However, the traditional relationship between the and ENSO has weakened since the mid-1970s, accompanied by a reduction in EAWM interannual variability (Wang and He, 2012). This weakening of the ENSO–EAWM linkage suggests that alternative oceanic drivers, particularly regional SST anomalies in the western North Pacific and its marginal seas, may have become increasingly important in modulating winter climate variability. Therefore, understanding the mechanisms governing global and regional interdecadal winter temperature variability, particularly those linked to regional SST forcing, is essential for improving climate prediction and supporting socio-economic planning and adaptation strategies.

2. Methods

We used the Hadley Centre Sea Ice and Sea Surface Temperature dataset (HadISST), which features a spatial resolution of $1^\circ \times 1^\circ$ and spans from 1870 onwards (Rayner et al., 2003). To assess the robustness of our results, we also employed the monthly SST from the Centennial In Situ Observation-Based Estimates of the Variability of SST and Marine Meteorological Variables (COBE-SST 2) provided by the Japan Meteorological Agency (JMA), which has a resolution of $1^\circ \times 1^\circ$ and is available from 1850 onwards (Hirahara et al., 2014). The HadISST dataset was used to calculate the AMO indices by averaging the anomalies of the North Atlantic SST (0° – 70° N) after removing the linear warming trend (Enfield et al., 2001). The PDO indices were calculated by extracting the first Empirical Orthogonal Function (EOF1) of the SST poleward of 20° N in the Pacific Ocean, using the detrended SST (Mantua and Hare, 2002). The EAWM index (EAWMI) is defined as the difference in DJF-mean 300-hPa zonal wind averaged over 27.5° – 37.5° N, 110° – 170° E and 50° – 60° N, 80° – 140° E (Jhun and Lee, 2004).

The effects of ECSM and other modes on regional climate were examined using monthly temperature and precipitation data from the Climate Research Unit (CRU) TS4.06 dataset, which has a spatial resolution of $0.5^\circ \times 0.5^\circ$ and covers the period since 1901 (Harris et al., 2020). We calculated global monthly mean surface temperatures by weighting all grid cells from the CRU TS4.06 data by their respective areas. The atmospheric circulations associated with the ECSM and other modes were analyzed by calculating correlations with geopotential heights (GPH) at 200 and 850 hPa and with winds using the Twentieth Century Reanalysis V3, which has a spatial resolution of $1^\circ \times 1^\circ$ (Slivinski et al., 2019). Sensible heat flux (SH) and latent heat flux (LH) from Twentieth Century Reanalysis V3 were also utilized to analyze the link between EAWM and ECSM. The long duration of this dataset, spanning from 1836 to 2015, was leveraged to reveal robust long-term climate regimes with periods longer than 8 yr. The monthly mean outputs of CMIP6 simulations (Table S1) (Eyring et al., 2016) were analyzed for both the historical experiment (HIS) during 1850–2014 and the shared socio-economic pathway (SSP) 585 warming scenario experiment (SSP585) during 2015–2099.

We applied Empirical Orthogonal Function (EOF) analysis

(Lorenz, 1956) to the winter (December–February) SST over the global oceans for the period 1874–2019 to extract the dominant modes of interdecadal variability and their corresponding principal component (PC) time series. Prior to the EOF analysis, the SST was first low-pass filtered using an 8-year Lanczos filter (Duchon, 1979) to suppress dominant interannual variability associated with the El Niño–Southern Oscillation (ENSO), which typically operates on 2–7-year timescales. To examine variability on multidecadal timescales, the lowest-frequency variability was then removed by fitting and subtracting a quadratic polynomial (MacDonald and Case, 2005). Considering that the 8-yr low-pass filtered series substantially reduces the degrees of freedom of the data, the effective degrees of freedom are considered when calculating the significance of correlation or regression based on Student's t test, which is defined as follows:

$$N_e = \frac{N}{1 + 2 \sum_{i=1}^N r_a * r_b} \quad (1)$$

where N_e is the effective degrees of freedom, N is the length of the time series and r_a and r_b are the i th-order autocorrelations for time series of a and b , respectively (Quenouille, 1952). Wavelet analysis was employed to assess periodic patterns in the time-frequency domain, with significance estimated against a red noise background (Torrence and Compo, 1998). Time-varying correlations at different timescales were evaluated using Wavelet Coherence (WTC) analysis (Grinsted et al., 2004).

3. Results

3.1 The East China Sea Mode (ECSM)

To emphasize interdecadal variability, we used the 8-year low-passed SST data to minimize the influence of the dominant interannual mode associated with the ENSO, which operates on a 2–7 yr periodicity (Timmermann et al., 2018). The leading Empirical Orthogonal Function (EOF1) of the filtered winter SST data explains 26.2% of the total variance and reveals peak loadings over the East China Sea (Fig. 1A), which we identify as the East China Sea Mode (ECSM). The ECSM is particularly robust and prominent during winter (Appendix Fig. S1), but it remains absent in other seasons (Figs. S2–S4), indicating that the ECSM is a winter-specific mode operating on interdecadal timescales. This finding aligns with the limited influence of ENSO on the East China Sea, as the wave train generated by ENSO typically propagates into the northeastern Pacific (Fang et al., 2019; Cai et al., 2023; Alizadeh, 2024), and the ENSO's effects are generally confined to subtropical regions (south of 35° N) (Fang et al., 2021; Alizadeh, 2024).

We used SST data from a defined region (110° – 130° E, 15° – 35° N) to represent the ECSM, which shows correlations with SST patterns closely resembling those of EOF1 (Fig. S5). For comparison, the second EOF (EOF2), accounting for 18.0% of the variance, displays peak loadings over the central and eastern North Pacific (Fig. 1B), consistent with the Pacific Decadal Oscillation (PDO) (Mantua and Hare, 2002). Both modes exhibit strong fluctuations on interdecadal scales (Fig. 1C and 1D); however, the ECSM is characterized by dominant periodicities near 7–8 and 40–60 yr (Fig. S6A), highlighting its distinct temporal behavior. Compared with the PDO and the Atlantic Multidecadal Oscillation (AMO), the ECSM exhibits an intermediate multidecadal timescale, and demonstrates persistent

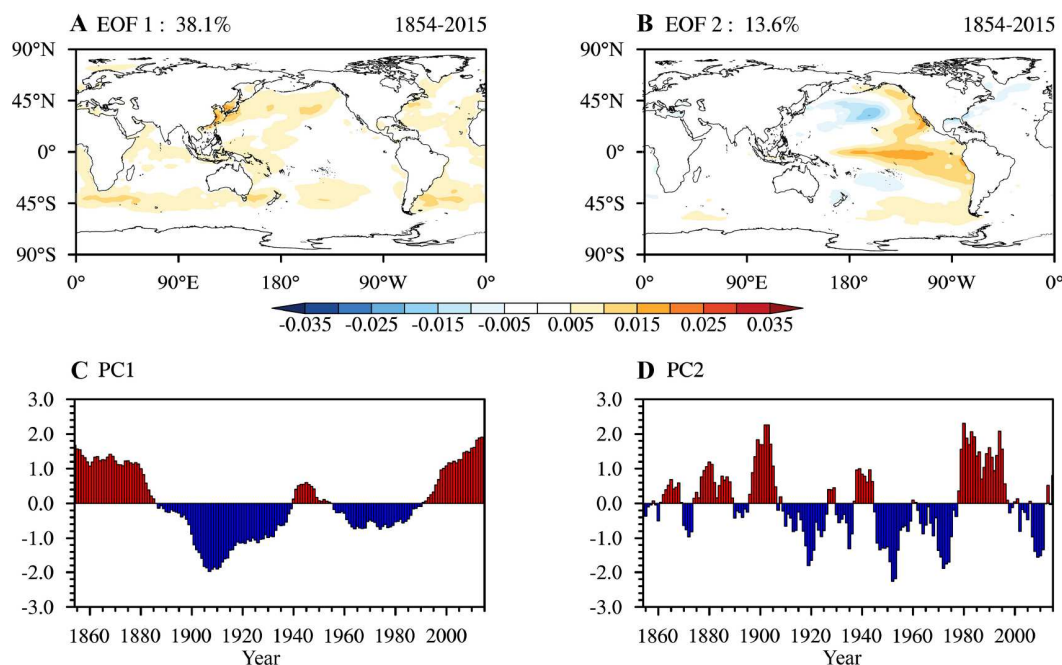


Fig. 1 The leading mode of the interdecadal winter sea surface temperature (SST). The (A and B) first two leading Empirical Orthogonal Functions (EOF1 and EOF2) of SST and (C and D) principal components (PC1 and PC2).

coherence with the PDO at periods longer than ~ 40 yr, albeit with a phase offset (Fig. S6B and S6D) (Schlesinger and Ramankutty, 1994; Enfield et al., 2001; Mantua and Hare, 2002; MacDonald and Case, 2005). These relationships indicate that, while the ECSM is not independent of other large-scale modes, it represents a distinct winter-specific interdecadal SST mode centered in the western North Pacific.

Previous studies have also argued that other regional SST modes in the Pacific basin, such as the North Pacific Gyre Oscillation (NPGO) (Di Lorenzo et al., 2008), variability of the western Pacific warm pool (Li et al., 1999), and the Kuroshio Extension (Qiu and Chen, 2005), also represent important aspects of Pacific climate dynamics. However, Fig. 1 shows that SST anomalies associated with the Kuroshio Extension, the western Pacific warm pool, and the NPGO regions do not exhibit prominent signals in the leading two EOF modes. This implies that, on interdecadal timescales, the ECSM and PDO may play a more dominant role in shaping large-scale winter SST variability than these other regional modes.

3.2 The ECSM is strongly affected by the East Asian Winter Monsoon (EAWM)

A positive phase of the ECSM (higher-than-normal SST) is strongly associated with southeasterly wind anomalies from the surface to the upper atmosphere over northeastern Asia (Fig. 2A and 2B), a hallmark of a weakened East Asian Winter Monsoon (EAWM) (Jhun and Lee, 2004; Li and Yang, 2010; Ma and Chen, 2023). The weakening of the EAWM is linked to a corresponding weakening of the Aleutian Low (Dong et al., 2023), as evidenced by the anti-cyclonic correlation pattern over the northern Pacific (Fig. 2A and 2B). In contrast, the wind anomalies associated with the PDO exhibit a cyclonic pattern over the northern Pacific (Fig. 2C and 2D), indicating a deepening of the Aleutian Low. This

PDO-related circulation is primarily confined to the eastern North Pacific, highlighting a spatial structure that differs markedly from the ECSM-associated wind patterns. These contrasts further underscore the distinct role of the ECSM in linking the East Asian winter monsoon to large-scale winter atmospheric circulation.

The influence of the EAWM (Jhun and Lee, 2004) on the ECSM is supported by the strong correlation ($r = -0.67$, $p < 0.001$) between the two indices (Fig. 3A). Additionally, strong correlations between SST and the EAWM are observed in the East China Sea (Fig. 3B), aligning with the regions influenced by the ECSM (Fig. 3C). The cold air masses transported by an enhanced EAWM can cool the sea surface in the East China Sea by enhancing the upward sensible heat flux from the ocean to the atmosphere (Fig. 3D). Moreover, the intensified northerly surface winds associated with an enhanced EAWM can increase evaporation by enhancing near-surface wind speed and turbulent moisture exchange between the ocean and the overlying cold, dry continental air, thereby enhancing latent heat flux from the sea surface and leading to further cooling of the East China Sea (Fig. 3E). The ECSM effectively reflects large-scale temperature variations as it is driven by the EAWM, one of the most dynamically intense winter circulation systems in the Northern Hemisphere (Johnson et al., 2018; Duan et al., 2013), and a primary source of winter coldness (Shi et al., 2023).

3.3 ECSM excites circumglobal interdecadal teleconnections

Positive ECSM anomalies lead to above-normal geopotential heights (GPHs) over northeastern Asia through air-sea interactions (Fig. 4A). These elevated GPHs over northeastern Asia are part of a wave train that propagates to Alaska, North America, Europe, Central Asia, and the Indian subcontinent (Fig. 4A). This wave train pattern represents the dominant teleconnection on

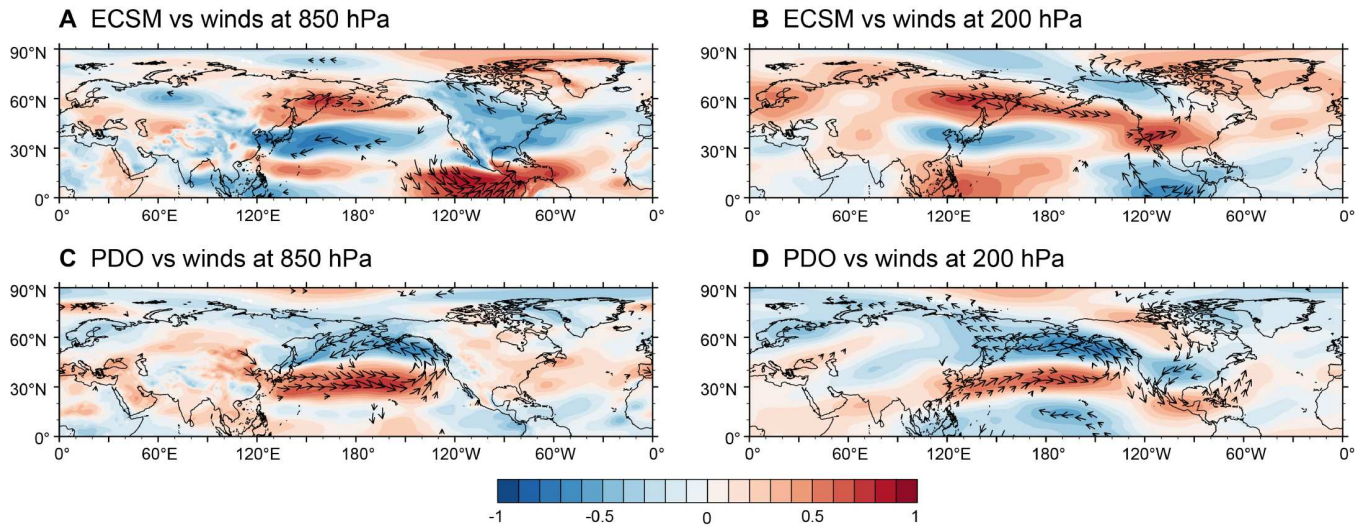


Fig. 2 Wind fields associated with the East China Sea Mode (ECSM). Panels show the correlations between the ECSM and wind fields at (A) 850 hPa and (B) 200 hPa, and between the Pacific Decadal Oscillation (PDO) and wind fields at (C) 850 hPa and (D) 200 hPa. Shading represents the correlation values, while wind vector length indicates wind strength. All data were 8-year low-pass filtered and detrended. Wind vectors are shown only where the regressions are statistically significant at the 95% confidence level based on the Student's *t* test.

interdecadal timescales during winter, as indicated by the first leading EOF (EOF1) of the GPHs at 200 hPa (Fig. 4B). The dominant circumglobal interdecadal teleconnection generally agrees with previously identified patterns in the Northern Hemisphere (Ding and Wang, 2005; Yu et al., 2024).

The PDO exhibits the strongest correlations with GPHs over the northern Pacific Ocean and western North America (Fig. 4C), a pattern reminiscent of the Pacific-North America (PNA) teleconnection (Renwick and Wallace, 1996; Dong et al., 2024). This PNA-like correlation pattern is part of the second dominant teleconnection mode, as indicated by the second leading EOF (EOF2) of the GPHs (Fig. 4D). The teleconnection pattern associated with the PDO is spatially distinct from that of the ECSM. Similarly, the AMO is linked to the third leading teleconnection pattern in winter on interdecadal scales (Fig. 4E and 4F). The teleconnection pattern associated with the AMO resembles that of the ECSM. In summary, the ECSM excites dominant circumglobal interdecadal teleconnections that shape global climate, closely resembling the AMO-related teleconnection pattern but differing from the PDO-related pattern.

4. Discussion

4.1 Compensatory effects of the ECSM and PDO on winter temperature

The correlations between winter temperatures and the ECSM and PDO reveal distinct but complementary regional patterns (Fig. 5). The ECSM shows significant positive correlations with temperatures over eastern and southern Asia, central and eastern Europe, eastern North America, central Africa, and southeastern Australia (Fig. 5A). Regions experiencing ECSM-driven positive temperature anomalies are often associated with high-pressure systems (Fig. 4A), which enhance shortwave radiation and contribute to warmer conditions (Fig. 5A and Fig. S7). In contrast, the PDO shows significant positive correlations with temperatures in regions such as central Asia, northwestern

North America, subtropical southern Africa, and northeastern Australia—areas that do not exhibit significant correlations with the ECSM (Fig. 5B).

Due to the complementary interaction between the ECSM and PDO, their combined influence exhibits significant correlations with temperatures over a broader area than either the ECSM or PDO alone (Fig. 5C). The positive correlations of the combined ECSM and PDO with temperatures extend to regions such as eastern and central Asia, western North America, eastern Australia, southern Africa, and northern South America (Fig. 5C). The complementary relationships between the ECSM and PDO with temperatures mirrors the distinctive but complementary features of their teleconnection patterns (Fig. 4A–4D).

4.2 ECSM enhances the effect of AMO on winter temperature

The AMO shows significant positive correlations with temperatures in tropical and subtropical Asia, northern Europe, North America, and northern South America (Fig. 5D). The regions affected by the AMO largely overlap those influenced by the ECSM, consistent with their similar atmospheric teleconnection patterns (Fig. 4A, 4B, 4E and 4F). As a result, the combined effect of the ECSM and AMO amplifies the strength of these correlations in areas where the AMO exerts a strong influence, though it does not expand the affected regions beyond those influenced by the individual modes (Fig. 5E). As expected, peak correlations are observed between temperature and the combined influence of the ECSM, PDO, and AMO ($r=0.76$, $p=0.02$), covering the regions influenced by all three climate modes (Fig. 5F).

It has been suggested that both the AMO and PDO can excite atmospheric teleconnection wave trains, thereby modulating large-scale circulation and temperature patterns. Recent studies further indicated that the temperature influence of the AMO can be mediated through variations in the Atlantic Meridional Overturning Circulation (AMOC) (Shi et al., 2023). The quasi-periodic nature of the AMO has been attributed to delayed

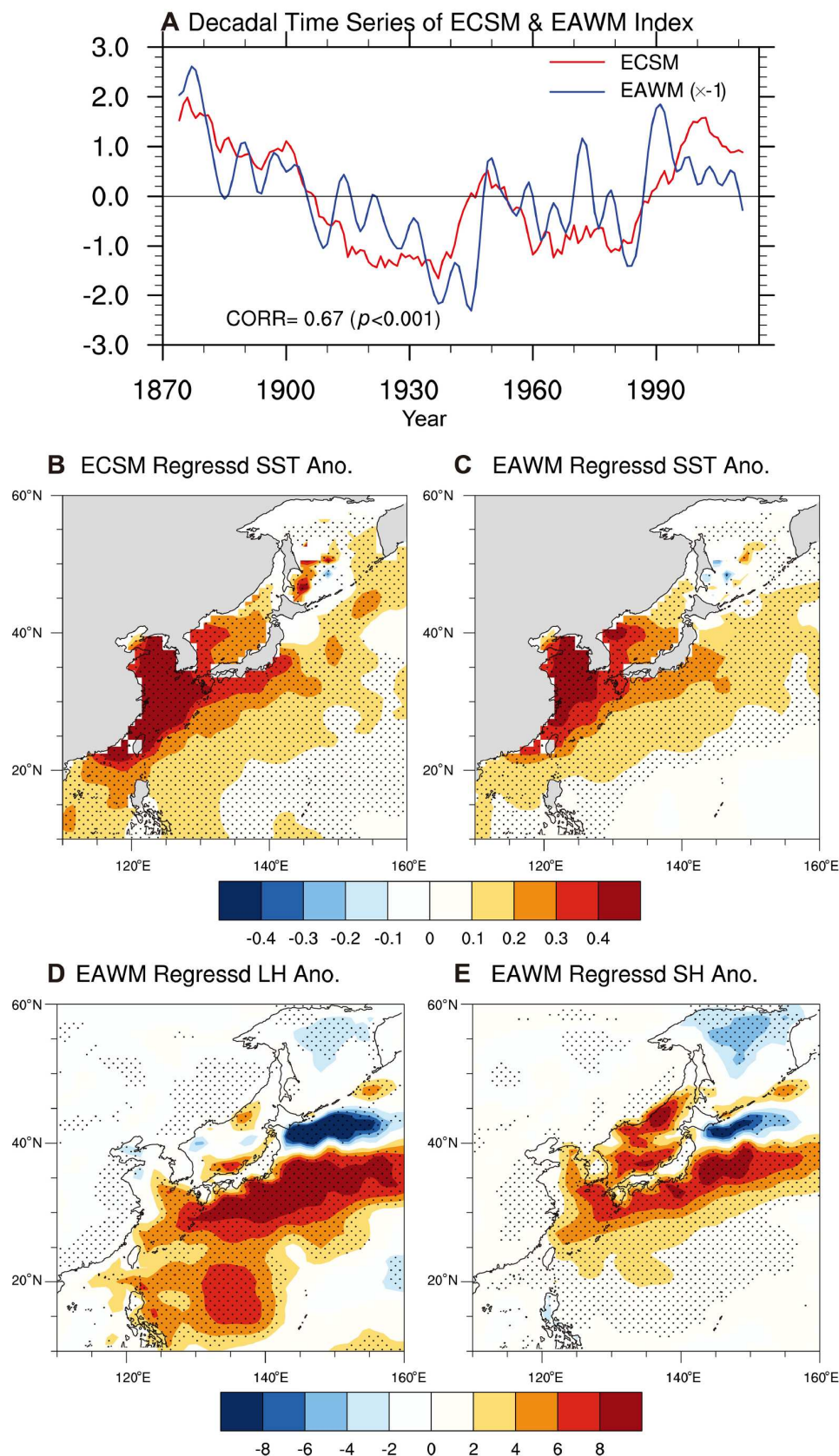


Fig. 3 The East Asian Winter Monsoon (EAWM) drives the East China Sea Mode (ECSM). (A) Comparison between the ECSM and EAWM indices, and regressions between (B) the EAWM and Sea Surface Temperature (SST) (shading; $^{\circ}\text{C}$), (C) the ECSM and SST, (D) the EAWM and latent heat flux (shading; W m^{-2}), and (E) the EAWM and sensible heat flux (shading; W m^{-2}). Positive sensible and latent heat flux anomalies correspond to upward fluxes (from the ocean to the atmosphere). The dots indicate regions where the regressions are statistically significant at the 95% confidence level based on the Student's t test.

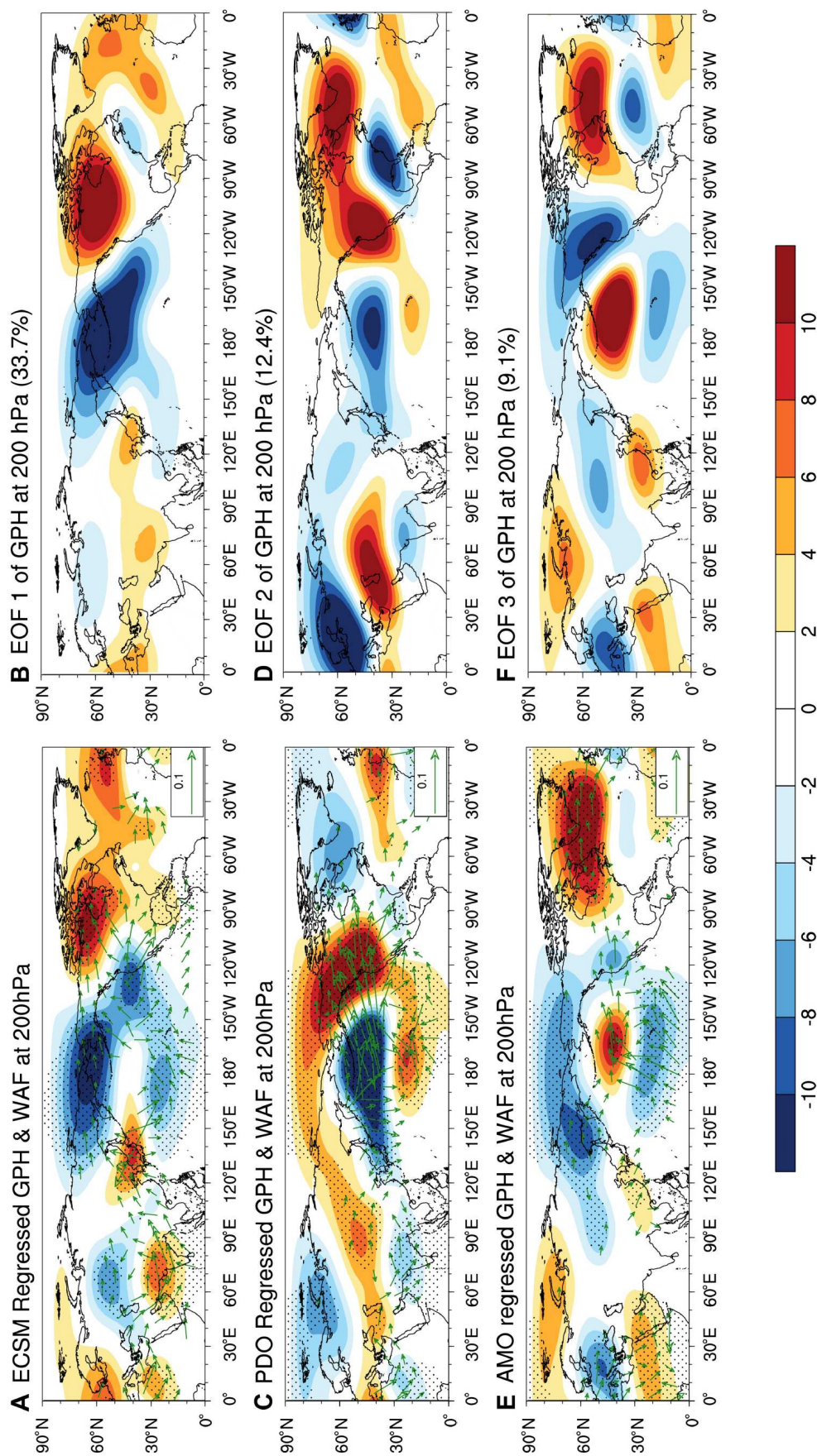


Fig. 4 Atmospheric teleconnections driven by climate modes. Regression between Geopotential Heights (GPHs) at 200 hPa (shading: m) and (A) the East China Sea Mode (ECSM), (C) the Pacific Decadal Oscillation (PDO), and (E) the Atlantic Multidecadal Oscillation (AMO). (B) The first, (D) second, and (F) third leading Empirical Orthogonal Function (EOF1, EOF2, and EOF3) patterns of the global GPHs at 200 hPa (shading: m). Vectors in (a, c, and e) represent Plumb wave activity flux (WAF) (Plumb, 1985), and direction indicates wave propagation. Vectors with both zonal and meridional components smaller than $0.015 \text{ m}^2 \text{ s}^{-2}$ are omitted. The data were detrended and processed with an 8-year low-pass filter. The dots indicate regions where the regressions are statistically significant at the 95% confidence level based on the Student's t test.

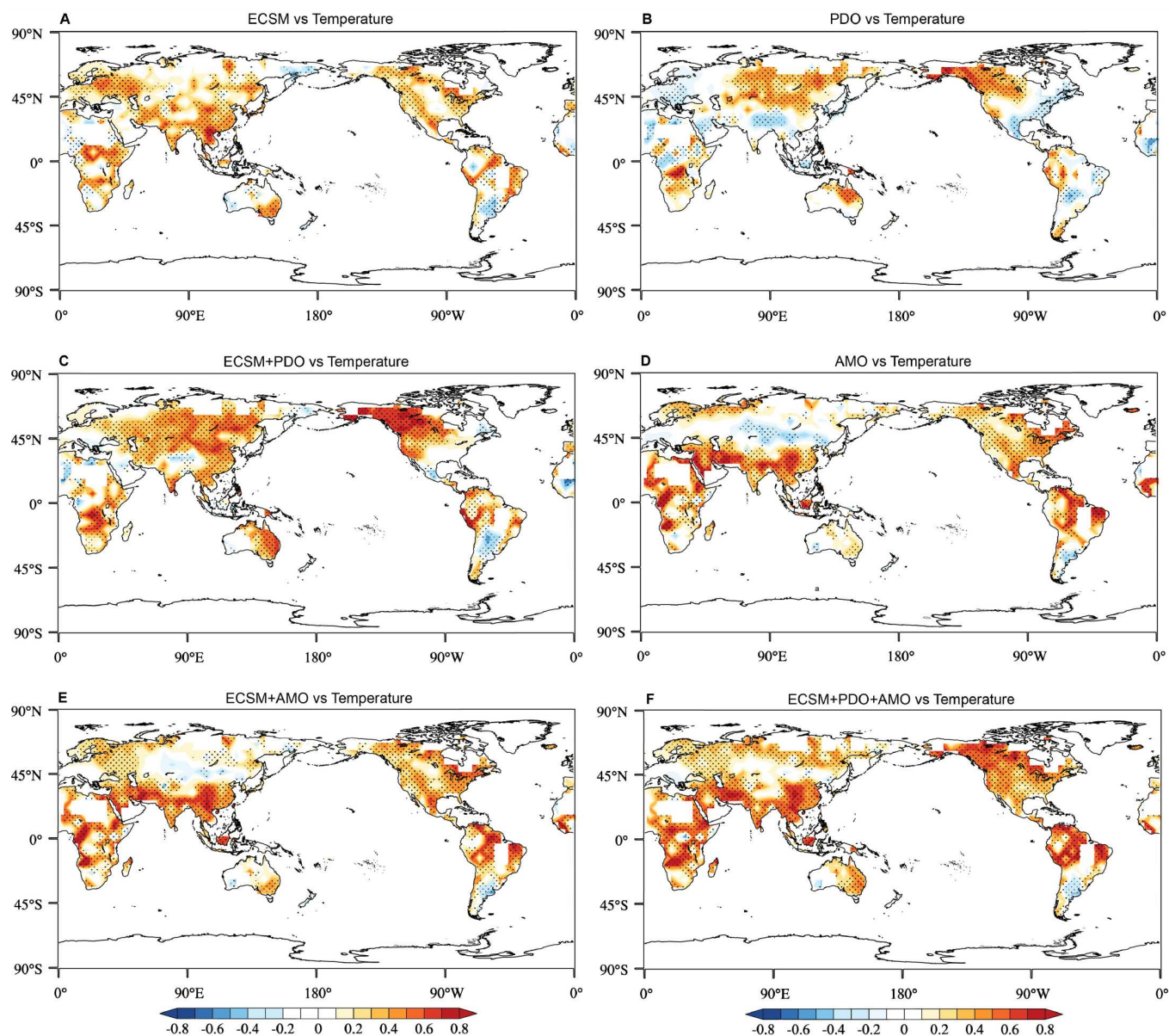


Fig. 5 Relationships between climate modes and winter (December–February) temperatures. Spatial correlation patterns between winter temperatures and (A) the East China Sea Mode (ECSM), (B) the Pacific Decadal Oscillation (PDO), (C) the combined ECSM and PDO, (D) the Atlantic Multidecadal Oscillation (AMO), (E) the combined ECSM and AMO, and (F) the combined ECSM, PDO, and AMO. All data were detrended and processed with an 8-year low-pass filter. The dots indicate regions where the correlation coefficients are statistically significant at the 95% confidence level based on the Student's *t* test.

feedbacks between the North Atlantic Oscillation (NAO) and AMOC, forming a coupled ocean–atmosphere oscillator (Sun et al., 2015). Through atmospheric teleconnections, these AMO-related circulation anomalies can influence extratropical and remote winter temperature patterns, providing a physical basis for the statistically robust AMO–temperature relationships identified here.

4.3 Increased influence of the ECSM on temperature in future projections

We utilized simulations from 40 models (Table S1) within phase 6 of the Coupled Model Intercomparison Project (CMIP6) framework (Eyring et al., 2016) to assess whether the ECSM will play a leading role in winter temperatures in future

scenarios, as it has during the observational period. The global mean temperature (GMT) and the mean SST of the ECSM, PDO, and AMO areas all exhibit strong upward trends in response to the ongoing increase in greenhouse gases (Fig. 6A). After removing the linear trend, the simulations successfully reproduce the historical interdecadal winter temperature patterns, including the warming of the 1930s and the cooling of the 1970s (Fig. 6B). Notably, future GMT trends are most closely aligned with the ECSM, particularly after ~2030, when the ECSM shows a clear upward trend, while the PDO and AMO do not (Fig. 6B).

5. Conclusions

Our study identified a winter-specific SST mode, the ECSM. The ECSM is a dominant modulator of global winter temperatures, as

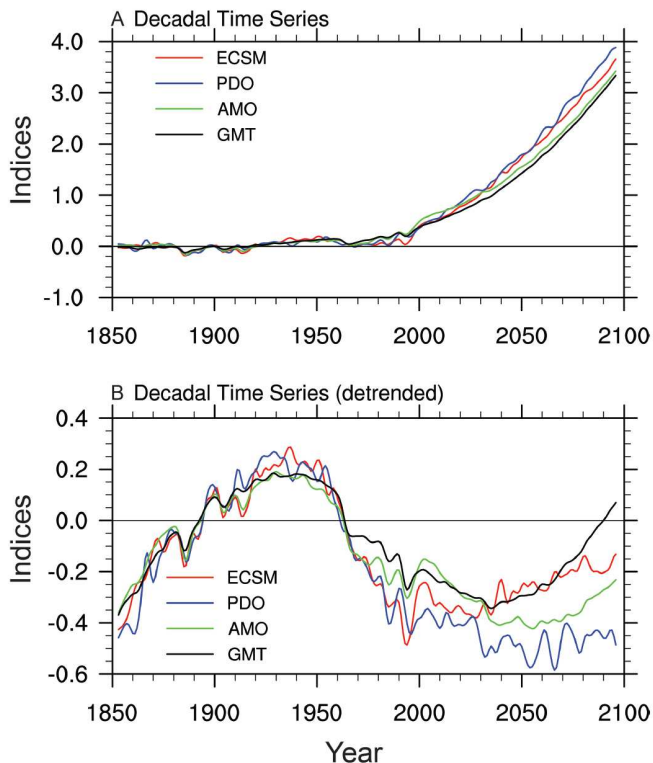


Fig. 6 Simulated influence of climate modes on global mean temperature (GMT). (A) Multimodel ensemble mean of decadal time series for the GMT and the Sea Surface Temperature (SST) of the areas used to define the East China Sea Mode (ECSM), Pacific Decadal Oscillation (PDO), and Atlantic Multidecadal Oscillation (AMO), and (B) the quadratically detrended multimodel ensemble mean of these time series. The simulation data were averaged from 40 models in Phase 6 of the Coupled Model Intercomparison Project (CMIP6) for historical runs and future scenarios spanning from 1850 to 2099.

revealed by both observations and simulations. The ECSM is regulated by the EAWM, a sensitive indicator of global winter temperature. On the other hand, the ECSM influences global winter temperatures by exciting the dominant circumglobal interdecadal teleconnection. The ECSM and PDO exhibit complementary characteristics in their relationships with teleconnection patterns and their effects on temperature. Consequently, the combined influence of the ECSM and PDO can explain a larger joint area affected by individual modes. In contrast, the ECSM and AMO are associated with similar teleconnection patterns and influence similar regions. Therefore, the combined effects of the ECSM and AMO amplify their impacts on temperatures in these overlapped areas. Previous studies generally consider the modulation of the eastern rim of the Pacific (PDO) on winter temperature, yet little attention was paid to its western part. Our study underscores the importance of considering both the east and west coasts of the North Pacific for improving the accuracy of global winter temperature projections.

In addition to internal climate modes, external forcings, particularly major volcanic eruptions, can induce pronounced regional cooling that persists for several years and may interact with or modulate the phasing of internal climate modes. Recent studies have shown that large volcanic eruptions, such as the Millennium eruption of the Changbaishan volcano, can exert substantial and spatially heterogeneous impacts on East Asian climate (Yang et al., 2024). Nevertheless, the results of this study

indicate that the ECSM, together with the PDO and AMO, represents a dominant mode of internally generated winter temperature variability. External forcings such as volcanic eruptions are therefore likely to modulate, rather than determine, the large-scale interdecadal patterns identified here, and their detailed interactions with internal climate modes warrant further investigation.

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Supporting information

The supporting information is available online at <http://earth.scichina.com> and <http://link.springer.com>. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

Compliance and ethics

The authors declare no conflict of interest.

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