

Multiscale Modulation of ENSO Characteristics and Teleconnections by Cross-Basin Climate Modes Under Global Warming

Zhiping Chen

zhpchen@ecut.edu.cn

East China University of Technology <https://orcid.org/0000-0002-3351-5831>

Bingkun Wang

bkwang@ecut.edu.cn

East China University of Technology

Zhuo Liu

lzhao@ecut.edu.cn

East China University of Technology

Yongkang Sun

yksun@ecut.edu.cn

East China University of Technology

Yu Gao

gaoyu@cumt.edu.cn

China University of Mining and Technology

Tieding Lu

tdlu@ecut.edu.cn

East China University of Technology

Research Article

Keywords: ENSO, Cross-basin climate modes, Global warming, Multiscale variability, Predictability

Posted Date: September 28th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10948403/v1>

License:  This work is licensed under a Creative Commons Attribution 4.0 International License.
[Read Full License](#)

Multiscale Modulation of ENSO Characteristics and Teleconnections by Cross-Basin Climate Modes Under Global Warming

Zhiping Chen^{1,2,3}, Bingkun Wang¹, Zhuo Liu¹, Yongkang Sun¹, Yu Gao⁴, Tieding Lu¹

¹ School of Surveying and Geoinformation Engineering, East China University of Technology, Nanchang, 330013, China

²Key Laboratory of Mine Environmental Monitoring and Improving around Poyang Lake of Ministry of Natural Resources, East China University of Technology, Nanchang, 330013, China

³Jiangxi Key Laboratory of Watershed Ecological Process and Information, East China University of Technology, Nanchang, 330013, China

⁴School of Environment and Spatial Informatics, China University of Mining and Technology, Xuzhou, 221116, China

Corresponding author: Zhiping Chen (zhpchen@ecut.edu.cn)

Abstract

Accelerated global warming is altering the characteristics of climate modes, such as the El Niño–Southern Oscillation (ENSO), and their associated teleconnections, thereby leading to more frequent extreme weather and climate events worldwide. This study investigates, on multiple time scales, changes in the characteristics and teleconnections of ENSO and other climate modes, including the Pacific Decadal Oscillation (PDO), Pacific Meridional Mode (PMM), Indian Ocean Dipole (IOD), Indian Ocean Basin-wide mode (IOB), Tropical North Atlantic (TNA), and Atlantic Meridional Mode (AMM). The results show that interannual variability is the dominant driver of these climate modes, while their long-term variations exhibit a strong response to the global warming signal. Under global warming, the promoting effect of ENSO on the PDO weakens, whereas its interactions with the PMM, IOD, IOB, TNA, and AMM are enhanced. Notably, the leading influence of ENSO relative to the PMM strengthens, and the leading influence of the TNA relative to ENSO also becomes more pronounced. Further analyses indicate that these enhanced interactions jointly lead to significant increases in ENSO amplitude, frequency, and asymmetry, accompanied by more frequent extreme El Niño events. In terms of predictability, ENSO shows a marked improvement in lead-1-year forecasts. After incorporating the above climate modes into the prediction framework, lead-2-year predictability increases by 0.07. Furthermore, under global warming, this predictability gain increases to 0.09. These results provide important theoretical support for understanding future climate events and improving ENSO forecast skill.

Keyword: ENSO; Cross-basin climate modes; Global warming; Multiscale variability; Predictability

1 Introduction

The El Niño–Southern Oscillation (ENSO) is one of the most influential climate modes in the global climate system (Timmermann et al. 2018; Cai et al. 2019, 2022). Through

teleconnections with other climate modes in the Pacific, Indian, and Atlantic Ocean basins, such as the Pacific Decadal Oscillation (PDO) (Zhang and Delworth 2016; Geng et al. 2019; Liang et al. 2024), Pacific Meridional Mode (PMM) (Fang and Yu 2020; Fan et al. 2023; Liu et al. 2024), Indian Ocean Dipole (IOD) (Wu et al. 2024; Zhao et al. 2025), Indian Ocean Basin-wide mode (IOB) (Zhang et al. 2021; Jin et al. 2023), Tropical North Atlantic (TNA) (Chen et al. 2021; Zhao et al. 2023), and Atlantic Meridional Mode (AMM) (Sun et al. 2024), among others (Fig. 2a), ENSO can modulate global sea surface temperature and wind fields and thereby favor more frequent extreme weather and climate events (Yeh et al. 2018; Cai et al. 2019). Meanwhile, the intensification of global warming not only alters the characteristics of climate modes such as ENSO, but also reshapes their teleconnections, increasing the dynamical complexity of ENSO and constraining its reliable monitoring and prediction (Geng et al. 2023; Chen et al. 2024c, a).

Recent studies have suggested that global warming may alter the atmospheric teleconnections and complexity of ENSO (Timmermann et al. 2018; Cai et al. 2022). Based on future simulations from CMIP5, Li et al. (2020) showed that intensified warming will significantly shorten the predictable lead time of the PDO and weaken its associated amplitude. Fan et al. (2021, 2022, 2023) found that, under global warming, the sensitivity of latent heat flux to zonal wind speed is enhanced, further strengthening the intensity of the PMM and its interaction with ENSO. In the Indian Ocean, positive IOD events become more frequent after warming and, after boreal winter, accelerate the decay of ENSO events through cold SST anomalies in the tropical Pacific, while also favoring the development of the subsequent ENSO event (Izumo et al. 2010; Jo et al. 2022; Sharma et al. 2023). The IOB has been suggested to contribute to the asymmetric life cycle of El Niño and La Niña (Cai et al. 2019; Jo et al. 2022). Atlantic climate modes can also interact with ENSO through atmospheric teleconnections. Ham et al. (2013) demonstrated that springtime TNA can act as a trigger for ENSO events. Intensified global warming strengthens the Pacific–Atlantic “atmospheric bridge” mechanism, thereby enhancing the linkage between eastern Pacific ENSO and the TNA (Park et al. 2023; Wang et al. 2024). In addition, Atlantic–Indian Ocean cross-basin interactions and subseasonal variability such as the Madden–Julian Oscillation may influence ENSO dynamics and predictability (Chang et al. 1997; Zhao et al. 2023).

Although previous studies have made substantial progress in understanding ENSO evolution and its multi-basin interactions, considerable uncertainty remains regarding the physical processes and response mechanisms linking ENSO with other climate modes across different time scales under global warming. On interannual time scales, ENSO is primarily governed by ocean–atmosphere recharge–discharge processes and equatorial wave dynamics (Ren and Jin 2013; Power et al. 2021). On decadal time scales, ENSO activity is modulated by low-frequency signals such as the PDO (Zhang and Delworth 2016; Geng et al. 2019). The PMM has been shown to be strongly related to central Pacific sea surface temperature variability on both interannual and decadal time scales (Tao et al. 2024). Studies have also indicated that intensified global warming shortens the period of the PDO and alters its amplitude across different time scales, implying that the responses of climate modes to the warming signal are strongly time-scale dependent (Di Lorenzo et al. 2023). Therefore, clarifying the physical processes associated with different climate modes on different time scales and identifying the scale-dependent responses to global warming are crucial for ENSO monitoring and prediction. However, the influence of global warming on climate modes in different ocean basins across different time scales remains uncertain (Cai et al. 2019; Hu et al. 2025). Previous studies have revealed the 2–7-yr periodicity of ENSO and the leading or teleconnection effects of individual

climate modes in different ocean basins on ENSO, but most have been limited to single-mode or single-time-scale analyses. Such limitations make it difficult to reveal how global warming affects changes in the interactions among climate modes in different ocean basins across time scales, and they constrain an integrated understanding of how different modes jointly influence ENSO.

Therefore, this study first reconstructs ENSO and six major climate mode indices based on historical ocean–atmosphere observations and reanalysis data for 1895–2024. Using 1960 as the dividing year, the study period is divided into the prewarming period (1895–1959) and the postwarming period (1960–2024). Then, multivariate empirical mode decomposition-normalized Hilbert transform (MEMD-NHT) is applied to decompose ENSO and climate-mode signals into multiscale components. By comparing differences in intensity, frequency, variability, and asymmetry among these modes, this study aims to reveal changes in the characteristics and interaction mechanisms of climate modes across different time scales under global warming, and to further assess the potential impacts of these changes on ENSO predictability, thereby providing a new theoretical basis for understanding the stability and predictability of the future climate system.

2 Materials and Methods

2.1 Data

SST data are obtained from the Hadley Centre Sea Ice and Sea Surface Temperature dataset (HadISST) provided by the Met Office Hadley Centre. This dataset provides continuous monthly mean sea surface temperature fields from 1871 to the present, with a spatial resolution of $1^\circ \times 1^\circ$ and global ocean coverage. Global surface temperature is taken from the HadCRUT5 dataset, which has a spatial resolution of $1^\circ \times 1^\circ$ and is constructed by combining land surface air temperature from CRUTEM5 with marine SST from HadSST4. It has been widely used to assess global warming trends. Wind-field data are derived from the Twentieth Century Reanalysis version 3 (20CRv3) released by the National Oceanic and Atmospheric Administration (NOAA) and the fifth-generation reanalysis dataset (ERA5) provided by the European Centre for Medium-Range Weather Forecasts (ECMWF). The 20CRv3 dataset provides 10-m wind vector data from 1806 to 2015 at a spatial resolution of $1^\circ \times 1^\circ$ and temporal resolutions ranging from 3-hourly to monthly means, making it suitable for analyzing long-term changes in background wind fields. ERA5 provides high-resolution wind-field data from 1940 onward, with a spatial resolution of $0.25^\circ \times 0.25^\circ$. Because 20CRv3 does not extend beyond 2015, ERA5 is used to extend the wind-field record from 2015 to 2024. The combined 1895–2024 record is then used to analyze changes in the characteristics and interactions of coupled SST–wind climate modes.

2.2 Reconstruction of Climate Mode Indices

To better understand changes in the characteristics and interaction mechanisms of ENSO and other climate modes under global warming, this study reconstructs climate mode indices for 1895–2024, including the ENSO, PDO, PMM, IOD, IOB, TNA, and AMM. These indices cover the Pacific, Indian, and Atlantic Ocean basins. To assess the reliability of the reconstructed indices, we compare them with the available corresponding climate mode indices provided by the NOAA Physical Sciences Laboratory (PSL) (Fig. 1). The Niño 3.4 index is defined as the 3-month running mean SSTA averaged over the Niño 3.4 region (5°S – 5°N , 170°W – 120°W ; Rayner et al., 2003). The reconstructed Niño 3.4 index is highly consistent with the PSL Niño

3.4 index, with a correlation coefficient of 0.98. The TNA index is defined as the area-averaged SSTA over the tropical North Atlantic region (5° – 25° N, 55° – 15° W; Enfield et al., 1999), and the reconstructed TNA index has a correlation of 0.99 with the PSL TNA index. The PDO index is taken as the first principal component of SST anomalies over the North Pacific region (20° – 70° N, 110° E– 100° W; Newman et al., 2016), and the reconstructed PDO index has a correlation of 0.96 with the PSL PDO index. The IOD index is defined as the difference in area-averaged SSTA between the western Indian Ocean (10° S– 10° N, 50° – 70° E) and the eastern Indian Ocean (10° S– 0° , 90° – 110° E), and its correlation with the PSL IOD index is 0.98 (Saji et al. 1999). The PMM (21° S– 32° N, 175° – 265° E) and AMM (21° S– 32° N, 75° W– 15° W) indices are defined as the first principal components obtained from maximum covariance analysis (MCA) between detrended SSTA and wind fields (Fan et al. 2023; Sun et al. 2024). The common basis function (CBF) method is further applied to ensure the spatial consistency of the PMM and AMM patterns (Chen et al. 2024b). Their correlations with the PSL indices are 0.89 and 0.81, respectively. In addition, following the method of Zhao et al. (2025), the IOB index is reconstructed as the area-averaged SSTA over the Indian Ocean region (20° S– 20° N, 40° – 110° E). These results demonstrate that the reconstructed climate mode indices are reliable, thereby providing a robust data basis for the subsequent analyses.

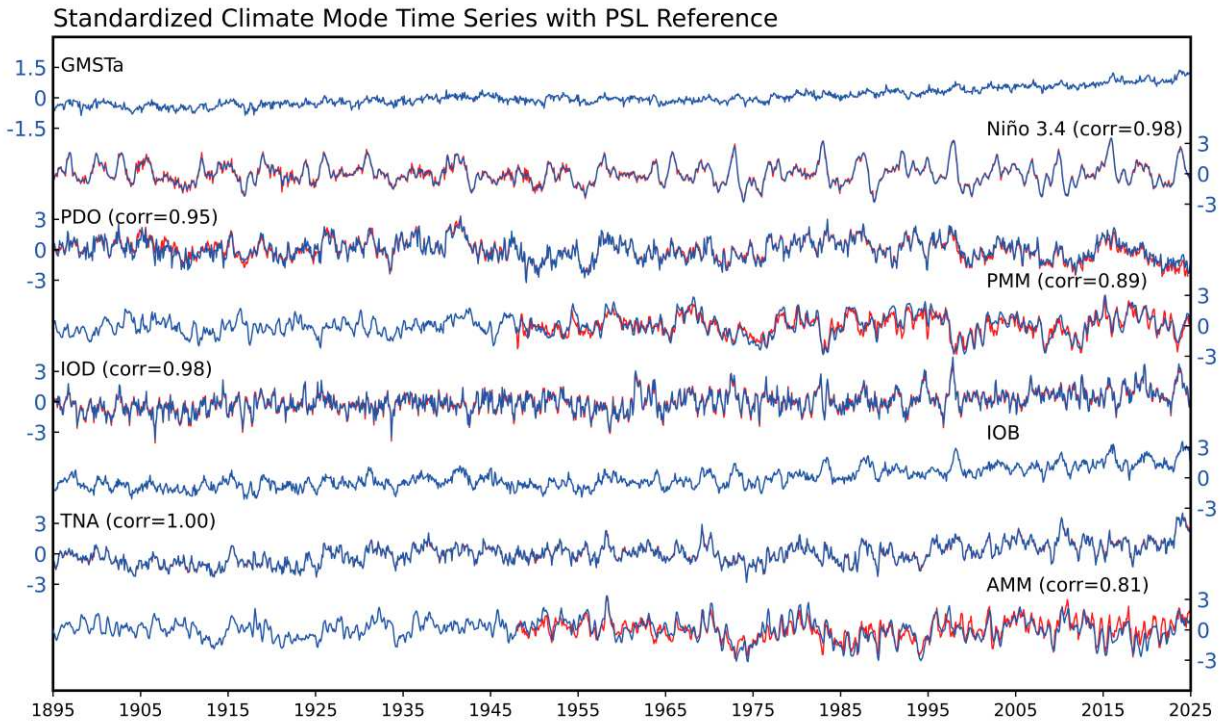


Fig. 1 Reconstructed standardized global warming signal and climate mode indices. The blue curves represent the climate mode indices reconstructed in this study, while the red curves represent the corresponding climate mode indices provided by NOAA PSL. The values in parentheses indicate the correlation coefficients between the reconstructed indices and the PSL indices, which are used to evaluate the consistency of the reconstructed indices. All correlation coefficients pass the 95% significance test.

2.3 Definition of the Global Warming Breakpoint

To examine changes in the characteristics and interaction mechanisms of ENSO and other climate modes after global warming, this study defines the global warming breakpoint based on global mean surface temperature anomaly (GMSTA). Cai et al. (2023) found that ENSO variability has strengthened since 1960, accompanied by more frequent strong El Niño and strong La Niña events. The IPCC Fifth Assessment Report also noted that global mean surface temperature changed substantially from the 1950s to the 1960s, with pronounced warming observed from the 1960s to the 1970s. Therefore, this study uses 1960 as the global warming breakpoint and divides the standardized ENSO and other climate mode indices for 1895–2024 into two equal-length periods: the prewarming period (1895–1959) and the postwarming period (1960–2024). These two periods are then compared to investigate how global warming has affected the characteristics and interaction mechanisms of ENSO and other climate modes.

2.4 Multiscale Joint Decomposition of ENSO and Climate Mode Indices Using MEMD-NHT

To examine changes in the characteristics and interactions between ENSO and multiple climate modes across different time scales, this study employs the MEMD-NHT method. Specifically, MEMD is first applied to jointly decompose ENSO and other climate mode indices, thereby overcoming several limitations commonly encountered in univariate EMD when applied to multiple time series, such as inconsistent numbers of modes, frequency mismatch, and misalignment along the time axis. In MEMD, multiple direction vectors are uniformly sampled in a high-dimensional space, and local envelope surfaces and local mean curves are constructed jointly for all variables (Huang et al. 1998; Mandic et al. 2013). This procedure ensures that each time series is decomposed into IMFs with the same frequency structure and phase alignment. Based on the ENSO index and climate mode indices from the three major ocean basins, we have:

$$X(t) = [x_{Ni\tilde{no}3.4}(t), x_{PDO}(t), x_{PMM}(t), x_{IOD}(t), x_{IOBW}(t), x_{TNA}(t), x_{AMM}(t)]^T, t = 1, 2, \dots, 1560 \quad (1)$$

Where $X(t)$ denotes the collection of multiple time series, $x(t)$ represents different climate mode indices, and t denotes time, with corresponding to the period from January 1895 to December 2024.

MEMD then identifies extrema of the signal along multiple projection directions, interpolates the upper and lower envelopes, and calculates their mean to obtain a joint local mean curve. Through an iterative sifting procedure, the multivariate signal is decomposed into K IMFs and one residual term $r(t)$, satisfying:

$$X(t) = \sum_{k=1}^K c_k(t) + r(t) \quad (2)$$

where the k IMF component is expressed as:

$$c_k(t) = [c_k^{(Ni\tilde{no}3.4)}(t), c_k^{(PDO)}(t), c_k^{(PMM)}(t), c_k^{(IOD)}(t), c_k^{(IOBW)}(t), c_k^{(TNA)}(t), c_k^{(AMM)}(t)]^T \quad (3)$$

After the decomposition is completed, the normalized Hilbert transform (NHT) is further applied to the normalized IMFs to more accurately obtain their instantaneous frequencies and amplitudes. Compared with the conventional Hilbert transform, NHT can effectively reduce spectral leakage and boundary effects when analyzing nonstationary signals, and it provides more stable and reliable estimates of instantaneous frequency (Huang and Wu 2008; Mandal et al. 2024). Therefore, each IMF is first normalized to obtain the corresponding normalized IMF, as given in Eq. (4).

$$c_{norm}(t) = \frac{c(t)}{A(t)} \quad (4)$$

Then, Hilbert analysis is performed on $c_{norm}(t)$, in which the real-valued signal $c_{norm}(t)$ is mapped onto its analytic signal $z(t)$:

$$z(t) = c_{norm}(t) + i \cdot \hat{c}_{norm}(t) \quad (5)$$

where $\hat{c}_{norm}(t)$ is the Hilbert transform of $c_{norm}(t)$, defined as $\hat{c}_{norm}(t) = \frac{1}{\pi} P.V. \int_{-\infty}^{+\infty} \frac{c(\tau)}{t - \tau} d\tau$. $P.V.$ denotes the Cauchy principal value integral.

The analytic signal is then expressed in polar form as:

$$z(t) = A(t)e^{i\theta(t)} \quad (6)$$

where $A(t) = |z(t)| = \sqrt{c_{norm}^2(t) + \hat{c}_{norm}^2(t)}$ is the instantaneous amplitude, representing the energy intensity of the climate-mode signal at each time step; $\theta(t) = \tan^{-1}(\hat{c}_{norm}(t)/c_{norm}(t))$ is the instantaneous phase; and $\omega(t) = d\theta(t)/dt$ is the instantaneous frequency, characterizing the temporal evolution of the local oscillation of the climate-mode signal.

After jointly decomposing the multiple climate mode indices for 1895–2024 using the MEMD-NHT method, each climate mode is separated into 13 IMF components and one residual term. According to the approximate periods of the IMF components, these components are further reconstructed into five time-scale components: the intra-annual component C1, with periods shorter than 1 year (IMF1-4); the interannual component C2, with periods between 1 and 10 years (IMF5-8); the decadal component C3, with periods between 10 and 20 years (IMF9-10); the multidecadal component C4, with periods between 20 and 80 years (IMF11-13); and the long-term trend component C5 (IMF14). The multiscale components of the Niño 3.4 index are shown in Fig. 3b–f.

3 Results

3.1 Changes in ENSO and Ocean-Basin Climate Modes under Global Warming

To fully understand changes in the characteristics and interactions of ENSO and climate modes across different ocean basins, this study selects several major ocean-basin climate modes (Fig. 2a), including the PDO, PMM, IOD, IOB, TNA, and AMM. The results show that, under continued global warming, ENSO and other climate modes exhibit pronounced decadal changes in intensity, frequency, variability, and asymmetry (Fig. 2). These changes not only reflect the

nonlinear response of the climate system, but also reveal the sensitivity of coupled ocean–atmosphere processes to external forcing. In terms of intensity (Fig. 2b), El Niño event intensity shows a trend of $+0.001^{\circ}\text{C yr}^{-1}$, while La Niña event intensity shows a trend of $-0.003^{\circ}\text{C yr}^{-1}$, both indicating an enhancement. In terms of frequency (Fig. 2c), the occurrence frequencies of El Niño and La Niña events of different intensities increase markedly after global warming, with weak-to-moderate El Niño and La Niña events becoming more likely to develop into strong events, accompanied by an increased frequency of extreme El Niño events. For climate-mode variability (Fig. 2d), the variability of ENSO increases from 0.75 to 1.25 after global warming, and the variability of other ocean-basin climate modes also increases substantially, except for the PDO. The largest increases occur in the PMM, from 0.59 to 1.40, and the AMM, from 0.68 to 1.26, indicating that global warming enhances the instability of the global climate system. In terms of asymmetry (Fig. 2e), the asymmetry of ENSO and climate modes such as the PDO, IOD, and TNA becomes more positive after global warming, with ENSO increasing from 0.25 to 0.38. In contrast, the asymmetry of the PMM and AMM shifts to a negative phase, decreasing from 0.22 to -0.22 and from 0.15 to -0.16 , respectively. These results suggest that global warming substantially amplifies the nonlinear characteristics of the climate system and may thereby alter the teleconnections of ENSO and other climate modes.

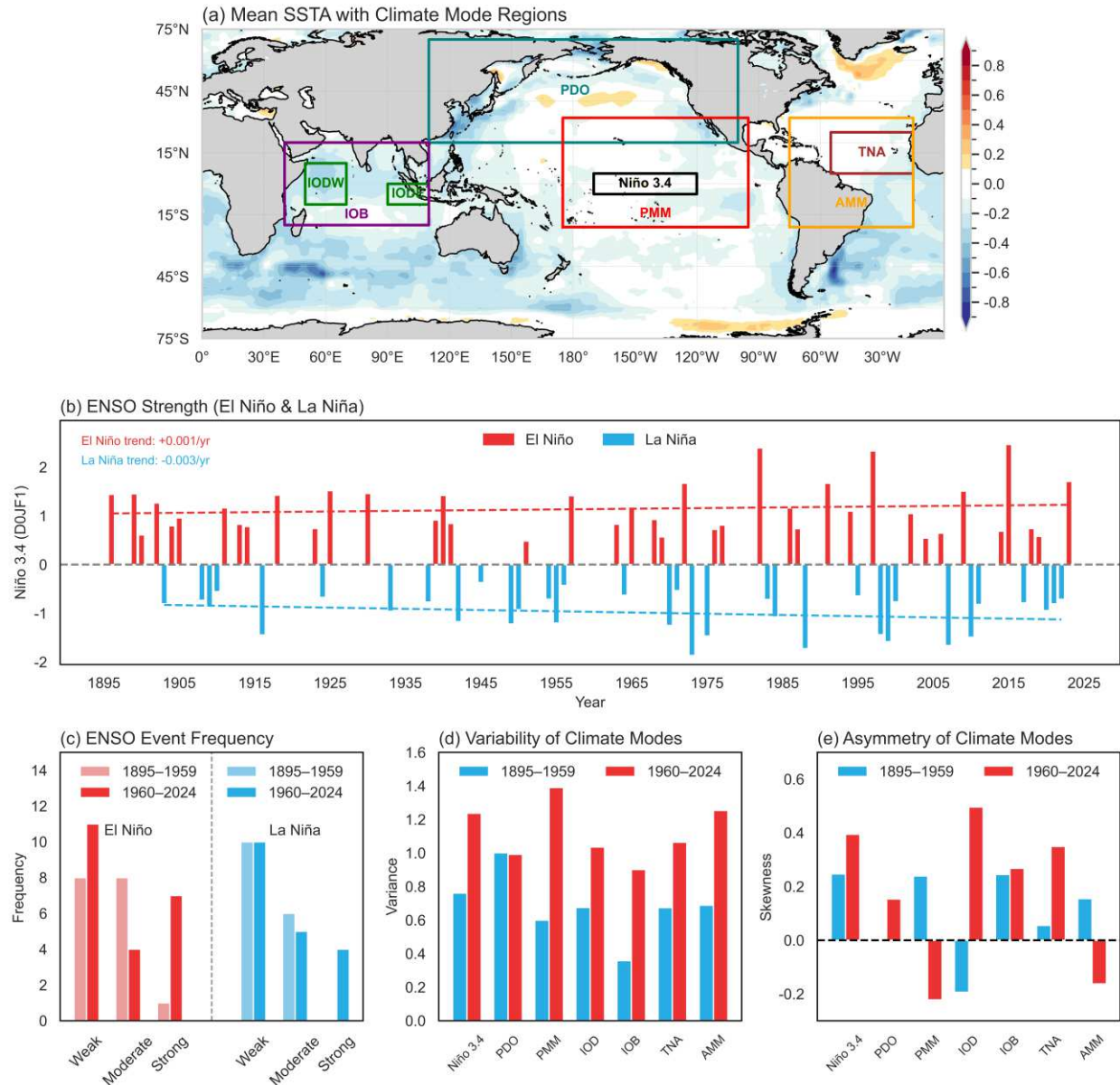


Fig. 2 Changes in the characteristics of ENSO and other climate modes before and after global warming. (a) Spatial domains of different climate modes. Shading indicates the multi-year mean sea surface temperature anomaly (SSTA) over 1895–2024; black: Niño 3.4, red: PMM, blue: PDO, green: IOD (IODW and IODE), purple: IOB, brown: TNA, yellow: AMM. (b) ENSO event intensity; dashed lines denote the linear trends for El Niño (red) and La Niña (blue), respectively. (c) Frequency of ENSO events of different intensities (thresholds: $|\text{Niño 3.4}| > 0.5/1.0/1.5^\circ\text{C}$ corresponding to weak/moderate/strong). (d) Variance of each climate mode; (e) Asymmetry of each climate mode. Note: the variance and asymmetry shown in (d) and (e) are calculated based on standardized mode indices;

3.2 Multiscale Changes in ENSO and Climate Modes under Global Warming

Global warming also affects the characteristics of ENSO and other climate modes across different time scales. Using the MEMD method, ENSO and six major ocean-basin climate mode

indices, including the PDO, PMM, IOD, IOB, TNA, and AMM, are jointly decomposed and then reconstructed into intra-annual components (C1), inter-annual components (C2), decadal components (C3), multi-decadal components (C4), and long-term trend components (C5). This allows us to examine changes in the characteristics of climate modes in different ocean basins across multiple time scales.

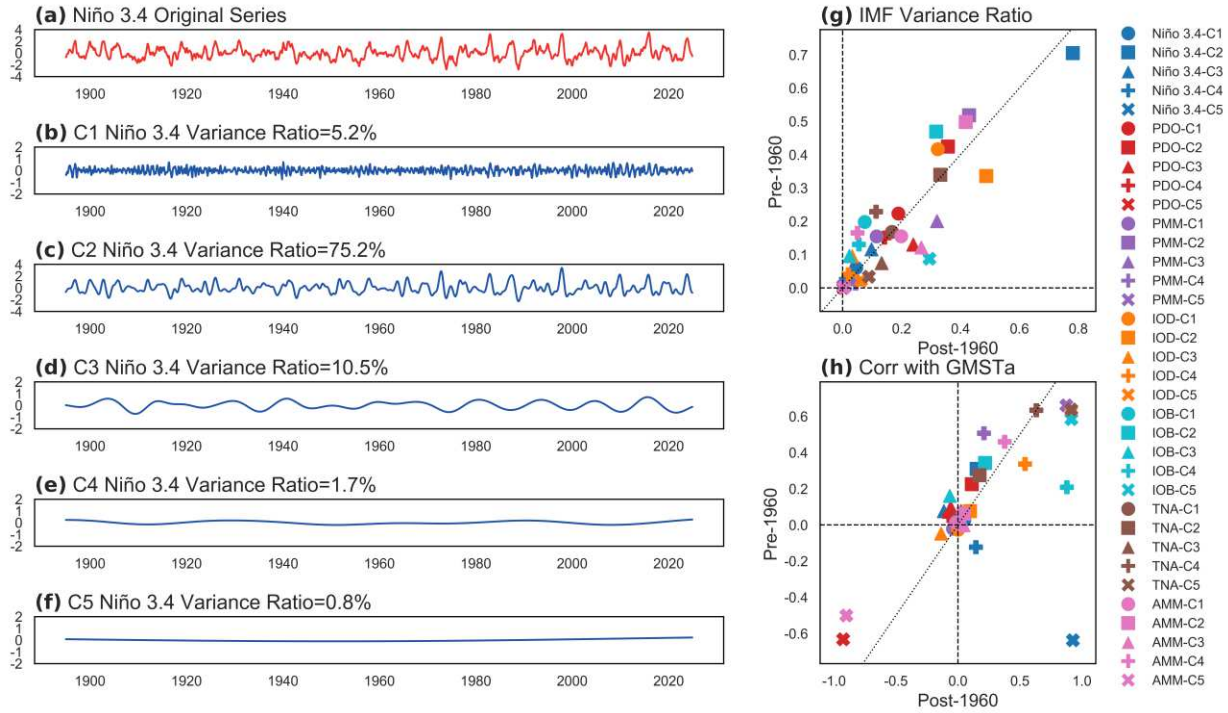


Fig. 3 MEMD decomposition of ENSO and statistical metrics linking ENSO to climate modes in different ocean basins. (a) shows the original Niño 3.4 time series. (b–f) display the Niño 3.4 components at different time scales. (g) shows, before and after global warming, the variance fraction of each time-scale component relative to the original climate-mode index; the three dashed lines denote the $x = 0$ axis, the $y = 0$ axis, and the $x = y$ line, respectively. Panel (h) shows, before and after global warming, the correlations between each time-scale component of the climate modes and the global warming signal; the three dashed lines denote the $x = 0$ axis, the $y = 0$ axis, and the $x = y$ line, respectively.

As shown in Fig. 3a–f, the variance contribution ratios of the different ENSO components are 5.2% for C1, 75.2% for C2, 10.5% for C3, 1.7% for C4, and 0.8% for C5. This indicates that ENSO is dominated by the interannual component C2, consistent with its characteristic 2–7-yr periodicity (Timmermann et al. 2018). Fig. 3g shows the variance contribution ratios of the IMF components of climate modes in different ocean basins before and after global warming, with the overall distribution approximately following the diagonal. After global warming, C2 remains the dominant source of variability for these climate modes. For the IOD, the intra-annual component is dominant before 1960, whereas after global warming its dominant component shifts to the interannual scale. As shown in Fig. 3h, the C5 components of all climate modes are highly correlated with the global warming signal, represented by the GMSTA. Before global warming, the absolute correlations between these climate modes and GMSTA are generally around 0.6, except for the AMM (0.37), with ENSO (-0.63), PDO (-0.65), and AMM (-0.35) negatively correlated with GMSTA. After global warming, the absolute

correlation coefficients between all climate modes and GMSTA exceed 0.88. ENSO, PMM, IOD, IOB, and TNA are positively correlated with GMSTA, whereas the PDO and AMM are negatively correlated with GMSTA. These results indicate that global warming exerts a pronounced influence on the long-term variability of climate modes across different ocean basins.

Table 1 Mean frequency and mean amplitude of the multi-time-scale IMF components of ENSO and climate modes in each ocean basin, before and after global warming, extracted using NHT. Values that are underlined and in bold indicate, in the comparison, a higher frequency and stronger intensity.

IMF	Mode	Niño 3.4		PDO		PMM		IOD		IOB		TNA		AMM	
		Freq	Amp	Freq	Amp	Freq	Amp	Freq	Amp	Freq	Amp	Freq	Amp	Freq	Amp
C1	1895-1959	<u>1.404</u>	0.259	<u>2.045</u>	<u>0.585</u>	<u>1.703</u>	0.380	<u>2.086</u>	0.660	<u>2.054</u>	<u>0.334</u>	<u>1.857</u>	0.428	<u>1.628</u>	0.413
	1960-2024	1.264	<u>0.307</u>	1.716	0.551	1.236	<u>0.511</u>	1.946	<u>0.723</u>	1.971	0.323	1.625	<u>0.532</u>	1.240	<u>0.632</u>
C2	1895-1959	0.304	0.918	0.332	<u>0.836</u>	<u>0.391</u>	0.712	<u>0.460</u>	0.606	<u>0.355</u>	0.509	<u>0.372</u>	0.603	<u>0.388</u>	0.725
	1960-2024	<u>0.349</u>	<u>1.209</u>	<u>0.357</u>	0.765	0.347	<u>0.972</u>	0.362	<u>0.802</u>	0.314	<u>0.656</u>	0.345	<u>0.746</u>	0.308	<u>0.950</u>
C3	1895-1959	0.068	0.384	0.071	0.498	0.075	0.437	<u>0.085</u>	<u>0.311</u>	0.062	<u>0.257</u>	<u>0.081</u>	0.289	<u>0.085</u>	0.377
	1960-2024	<u>0.075</u>	<u>0.454</u>	0.071	<u>0.551</u>	<u>0.083</u>	<u>0.913</u>	0.072	0.255	<u>0.076</u>	0.177	0.060	<u>0.408</u>	0.071	<u>0.660</u>

Global warming has altered both the variability of ocean-basin climate modes and the strength of their responses to the global warming signal. These changes may further affect the oscillation frequency and energy distribution of climate modes across multiple time scales. The variance contributions of ocean-basin climate modes are mainly concentrated in the intra-annual component C1, interannual component C2, and decadal component C3. Therefore, this section focuses on the changes in these climate modes on the three time scales under global warming. As shown in Table 1, after global warming, the frequency of the ENSO C1 component decreases from 1.404 to 1.264, and the C1 frequencies of the other climate modes also show a general slowdown. In terms of amplitude, ENSO increases markedly from 0.259 to 0.307, whereas the IOB changes only slightly, from 0.334 to 0.323. By contrast, the PMM, IOD, TNA, and AMM all show pronounced amplitude increases in the C1 component.

On the interannual time scale C2, the mean frequency of ENSO increases from 0.304 to 0.349 after global warming, while its amplitude increases substantially from 0.918 to 1.209. This further indicates that global warming shortens the interannual recharge–discharge cycle of ENSO and strengthens ocean–atmosphere coupling. After global warming, the PDO also exhibits an accelerated frequency on the interannual time scale, whereas the PMM, IOD, IOB, TNA, and AMM all show reduced interannual frequencies. From the amplitude perspective, the interannual amplitudes of ENSO, PMM, IOD, IOB, TNA, and AMM all increase after global warming, consistent with the changes in climate-mode variability shown in Fig. 2d. In contrast, the mean interannual amplitude of the PDO decreases, consistent with its intra-annual amplitude change. This is mainly because warming accelerates Rossby wave propagation, thereby increasing the PDO frequency while reducing its amplitude (Zhang and Delworth 2016; Li et al. 2020).

Moreover, although the interannual oscillation frequency of ENSO increases, the interannual frequencies of the PMM, IOD, IOB, TNA, and AMM decrease.

For the decadal component C3, the ENSO frequency increases from 0.068 to 0.075 after global warming, while its amplitude increases from 0.384 to 0.454, indicating both accelerated frequency and enhanced intensity. In terms of frequency, the decadal C3 component of the PDO shows no obvious change after global warming. The decadal C3 components of the PMM and IOB exhibit accelerated frequencies, whereas those of the IOD, TNA, and AMM show reduced frequencies. In terms of amplitude, the PDO and PMM both show enhanced C3 amplitudes after global warming, whereas the IOD and IOB both show weakened C3 amplitudes. The TNA and AMM, by contrast, both exhibit enhanced C3 amplitudes. These results suggest that climate modes within the same ocean basin show consistent changes on the decadal time scale. The Atlantic TNA and AMM both exhibit reduced frequencies and enhanced amplitudes across the intra-annual, interannual, and decadal time scales, indicating that global warming has increased the risk of extreme climate events over the tropical Atlantic region.

3.3 Effects of Global Warming on the Interactions between ENSO and Ocean-Basin Climate Modes

Teleconnections among climate modes exert substantial influences on the global climate system. After global warming, the teleconnections of ENSO and other ocean-basin climate modes may also change in response to changes in their intrinsic characteristics. Wavelet coherence analysis of the components between Niño 3.4 and multiple climate modes shows that the interactions between ENSO and other ocean-basin climate modes are mainly concentrated at periods of 1-10 years. This indicates that ENSO interacts significantly with other climate modes on interannual time scales, with the strongest coherence occurring between ENSO and the PDO and between ENSO and the IOB, and the weakest coherence occurring for the AMM. This is consistent with the result in Fig. 3g, which shows that the C2 interannual component dominates the variability of these climate modes.

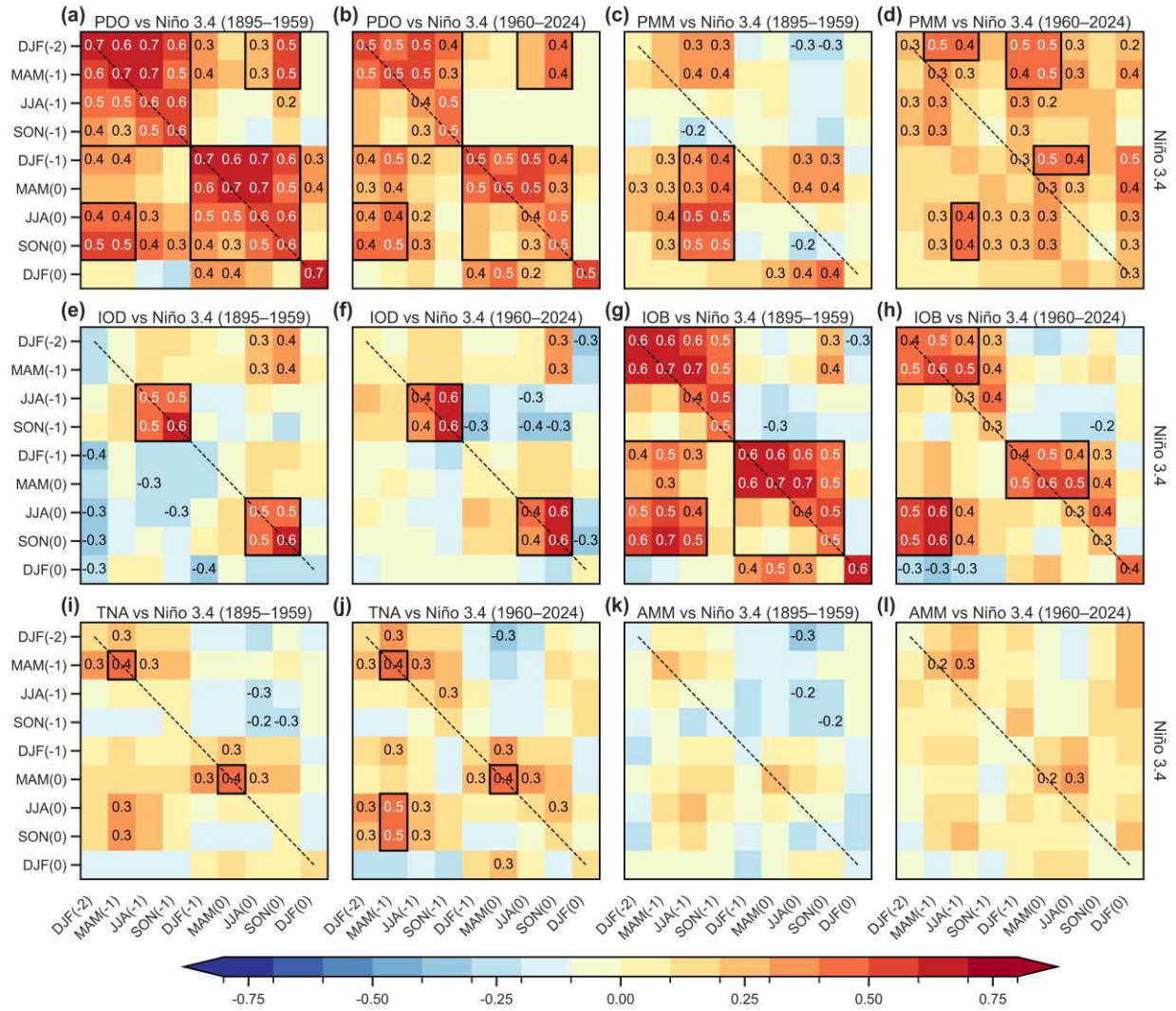


Fig. 4 Seasonal correlations between ENSO and each climate mode before and after global warming. (a, c, e, g, i, k) show the seasonal correlation matrices between ENSO and the respective climate modes before global warming, whereas panels (b, d, f, h, j, l) show the corresponding matrices after global warming. The y-axis denotes ENSO seasons and the x-axis denotes seasons of the other climate modes. Colored cells with correlation annotations pass the 95% confidence test. Cells along the black dashed line indicate no lead or lag, and the black boxed regions highlight relatively strong correlations.

Therefore, to further examine changes in the teleconnections between ENSO and other climate modes after global warming, seasonal lag correlations between ENSO and other climate modes are calculated for the prewarming and postwarming periods (Fig. 4). Before global warming, ENSO and the PDO exhibit significant covariability beginning in winter (DJF; black boxes in Fig. 4a). The correlations are stronger below the diagonal, indicating that the PDO is more strongly modulated by ENSO during their covariability, and this influence gradually decays by the following autumn (SON). In addition, ENSO in winter of the first year (DJF) and spring of the second year (MAM) exerts a significant regulatory effect on the PDO in summer (JJA) and autumn (SON) of the third year, with the influence becoming significant in summer

and peaking in autumn. Meanwhile, the PDO in winter of the first year (DJF) and spring of the second year (MAM) also significantly regulates ENSO in summer (JJA) and autumn (SON) of the third year, with significant correlations in summer and a peak in autumn. After global warming, the significant interaction between ENSO and the PDO remains evident (Fig. 4b), but its correlation strength weakens. Together with the reduced PDO amplitude on intra-annual and interannual time scales, this further confirms that the interaction between the PDO and ENSO weakens under global warming. For the PMM, there is no strong covariability between ENSO and the PMM before global warming (Fig. 4c), but the PMM in summer and autumn of the first year significantly and positively regulates Niño 3.4 in the subsequent winter. This influence peaks in the summer of the second year and decays in autumn. This is consistent with previous studies suggesting that the PMM acts as an important precursor of ENSO, mainly through a mechanism in which subtropical SST anomalies induce wind anomalies that excite equatorial Kelvin waves, thereby triggering SST responses in the eastern Pacific (Zheng et al. 2023). After global warming (Fig. 4d), however, the dominant role of ENSO in the ENSO–PMM interaction becomes stronger. Specifically, Niño 3.4 in winter of the first year positively regulates the PMM in the following two seasons and also shows a significant positive modulation of the PMM in winter of the second year. Although the influence of the PMM on ENSO still exists, it is substantially weaker than before global warming. This indicates that global warming has altered the dominant relationship in the ENSO–PMM interaction, with ENSO increasingly becoming the leading factor.

For the Indian Ocean, ENSO and the IOD exhibit significant covariability in summer before global warming (Figs. 3e,f), with the relationship peaking in autumn. In addition, Niño 3.4 in the previous year positively modulates the IOD in the current year, whereas the IOD in the previous year exerts a negative, albeit weak, modulation on Niño 3.4 in the current year. After global warming (Fig. 4f), the modulation of ENSO by the IOD in the following year loses significance, while the modulation of the IOD by ENSO is further strengthened. For the IOB, ENSO and the IOB exhibit significant covariability beginning in winter before global warming (Figs. 3g,h). This covariability is dominated by ENSO, which influences the IOB; the influence gradually weakens after the following spring and loses significance after autumn. In addition, the IOB in winter of the first year and spring of the second year (MAM) significantly and positively modulates ENSO in summer and autumn of the third year, with the influence becoming significant in summer (JJA) and peaking in autumn (SON). After global warming, the significant interaction between ENSO and the IOB remains evident (Fig. 4h), but the correlation strength decreases. The significant positive modulation of ENSO in summer (JJA) and autumn (SON) of the third year by the IOB in winter (DJF) of the first year and spring (MAM) of the second year also persists.

For the Atlantic Ocean, ENSO and the TNA exhibit significant covariability in spring before global warming (Figs. 3i,j). In addition, the TNA in spring of the first year exerts a weak positive modulation on ENSO in summer and autumn of the second year. After global warming (Fig. 4j), the dominant influence of ENSO on the TNA is further enhanced, and the positive modulation of ENSO by springtime TNA in the preceding year becomes significant. For the AMM (Figs. 3k,l), no significant modulation with ENSO is evident before global warming. After global warming, however, the global influence of ENSO is further intensified, causing the AMM to also be modulated by ENSO to some extent.

3.4 Spatial Effects of Global Warming on the Interactions between ENSO and Climate Modes

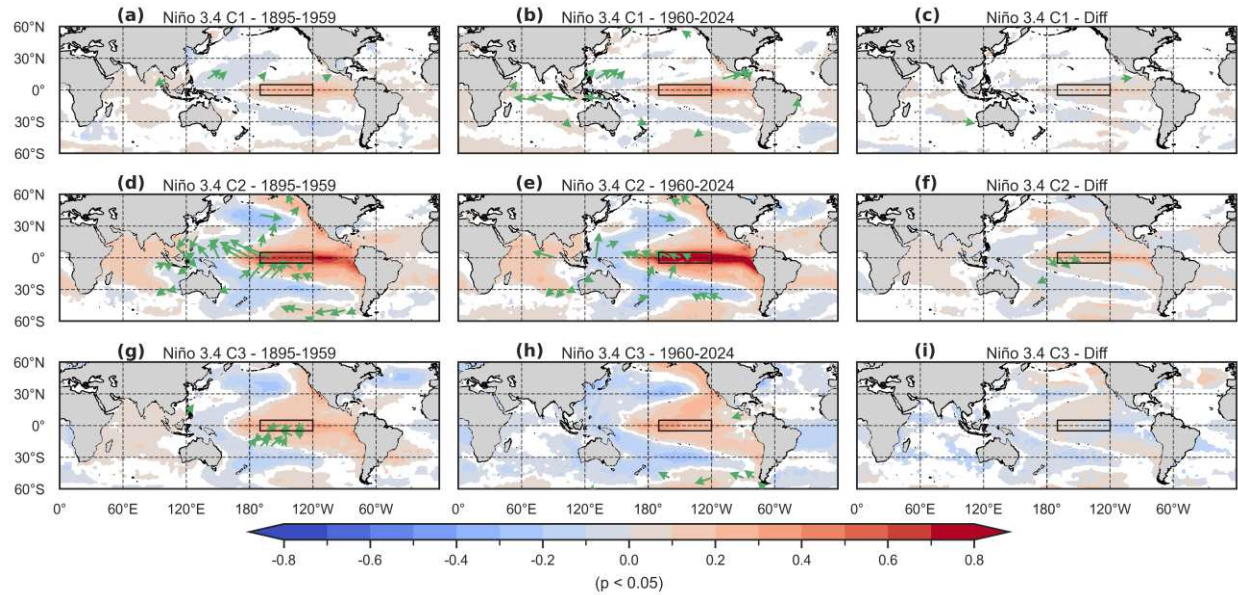


Fig. 5 Global responses to the multi-time-scale Niño 3.4 components before and after global warming ($^{\circ}\text{C s.d.}^{-1}$). Panels (a, d, g) show the spatial response patterns before global warming. Panels (b, e, h) show the corresponding patterns after global warming. Panels (c, f, i) show the differences in the spatial responses (after minus before global warming). The black box marks the Niño 3.4 region, grey shading indicates land areas, the colorbar denotes the magnitude of the SST response, and green arrows indicate the wind-field response.

To further quantify the spatial changes in the interactions between ENSO and other climate modes after global warming, we calculate the spatial responses of sea surface temperature and wind fields associated with each climate mode. The spatial response changes of ENSO on the intra-annual, interannual, and decadal time scales are shown in Fig. 5. On the intra-annual time scale C1, ENSO exhibits a weak SST response over the central and eastern tropical Pacific before global warming (Fig. 5a), whereas after global warming (Fig. 5b), the SST response of ENSO over the central and eastern tropical Pacific becomes stronger, accompanied by an enhanced wind-field response near the equatorial Indian Ocean. On the dominant interannual time scale C2, the global response of ENSO is most pronounced. Before warming (Fig. 5d), the interannual spatial response of ENSO exhibits a typical horseshoe-like structure, characterized by a strong positive response over the central and eastern Pacific. The wind-field response shows anomalous westerlies over the North Pacific, anomalous easterlies over the South Pacific, and interactions with the Indian Ocean through wind anomalies along the equator, whereas the response over the Atlantic is relatively weak. After warming (Fig. 5e), the positive SSTA response of ENSO over the central and eastern Pacific is further enhanced, but the meridional wind-anomaly response extending toward the North Pacific weakens, accompanied by a reduction in the negative SST response over the North Pacific. This further reflects the tendency for a weakened response of the North Pacific, such as the PDO, to ENSO under global warming. On the decadal time scale C3, ENSO exhibits a typical positive SSTA response over the central and eastern Pacific, together with negative responses over the North and South Pacific, before warming (Fig. 5g). After warming (Fig. 5h), however, the central Pacific SST

response of ENSO on the decadal time scale becomes stronger, whereas the eastern Pacific SST response weakens. This may be one reason why the frequency of CP ENSO events increases more rapidly than that of EP ENSO events after global warming (Cai et al. 2021). Overall, Fig. 5 shows that the spatial responses of climate modes are still manifested primarily on the interannual time scale, consistent with the preceding results.

Given the dominant role of the interannual time scale in climate modes, the following analysis presents only the interannual spatial responses of climate modes in each ocean basin. The spatial responses of the other climate modes before and after global warming are shown in Fig. 6. On the interannual C2 component, the PDO spatial response before global warming exhibits a typical horseshoe-like structure, with a significant positive SST response over the central and eastern equatorial Pacific, reflecting its strong coupled ocean–atmosphere linkage with ENSO. The PDO also shows pronounced positive SST responses over the Indian and Atlantic Oceans. After global warming, the meridional northerly wind response associated with the PDO weakens, and the negative SST response over the North Pacific is reduced (Fig. 6b). This suggests that global warming may weaken the interaction between the PDO and ENSO through Rossby wave processes, consistent with the decreased PDO amplitude on the interannual time scale shown in Table 2. Meanwhile, the further enhancement of the PDO-related SST response over the central and eastern Pacific indicates that, as the PDO weakens, the frequency and intensity of ENSO events may further increase after global warming. For the PMM, its interannual spatial response is mainly confined to the Pacific sector, characterized by a dipole structure consisting of a positive SST response extending from the eastern North Pacific to the central-western equatorial Pacific and a negative SST response over the eastern equatorial Pacific. After global warming (Fig. 6e), the positive SST response of the PMM over the central-western equatorial Pacific strengthens, while the negative SST response over the eastern equatorial Pacific also intensifies. This indicates that the interaction between the PMM and ENSO is enhanced under global warming, together with an increased asymmetric modulation of ENSO by the positive and negative phases of the PMM. In addition, the PMM-related SST response over the northern North Pacific also shows a positive enhancement.

For the Indian Ocean modes, the interannual C2 spatial response of the IOD before global warming displays a clear dipole structure, characterized by a negative SST response over the eastern pole of the Indian Ocean and a positive SST response over the western pole. The IOD also shows a positive SST response over the central and eastern equatorial Pacific. In addition, anomalous easterly wind responses occur over the central and North Pacific. After global warming (Fig. 6h), the SST response over the western Indian Ocean strengthens, suggesting that global warming makes the formation of negative IOD events more difficult and favors more frequent and stronger positive IOD events, consistent with the enhanced positive asymmetry of the IOD shown in Fig. 2d. For the IOB, before global warming, its interannual component shows significant positive SST responses over the Indian Ocean, central-eastern Pacific, and Atlantic Ocean, accompanied by a pronounced northerly wind response over the equatorial Pacific. After global warming (Fig. 6k), the positive SST response of the IOB increases over the western Indian Ocean, and its SST response over the central and eastern Pacific strengthens substantially on the interannual time scale, reflecting an enhanced cross-basin influence of ENSO after global warming. The IOB also shows a weakened wind-field response, similar to the IOD, which may be related to the weakening of the Walker circulation under global warming and its effect on the interaction between ENSO and the Indian Ocean. In addition, the Atlantic SST

response associated with the interannual IOB further strengthens, suggesting that the IOB may exert an enhanced influence on climate modes in other ocean basins through the Hadley and Walker circulations. It is worth noting that previous studies have shown that the interaction between ENSO and Indian Ocean climate modes is modulated by the PDO. Therefore, the weakened PDO amplitude (Fig. 6b), together with the reduced negative SST responses of the IOB and IOD over the North Pacific after global warming, suggests that changes in the ENSO–Indian Ocean interaction may be related to the weakening of the PDO.

For the Atlantic modes, the interannual C2 component of the TNA exhibits a horseshoe-like structure within the Atlantic basin, together with significant positive SST responses over the central-eastern equatorial Pacific and the Indian Ocean. By contrast, the AMM displays a PMM-like spatial response within the Atlantic basin, without evident Pacific or Indian Ocean responses. After global warming (Fig. 6n), the positive SST responses of the TNA over the equatorial Atlantic and eastern Pacific are further enhanced, whereas the AMM (Fig. 6q) is mainly characterized by further strengthening of both positive and negative SST responses within the Atlantic basin. These results indicate that global warming enhances the internal variability of the TNA and AMM, and that the interaction between the TNA and ENSO also becomes stronger, whereas the interaction between the AMM and ENSO remains relatively weak. After global warming, the positive SST response of the TNA over the western Indian Ocean also strengthens, indicating that cross-basin interactions among Atlantic, Pacific, and Indian Ocean climate modes are gradually enhanced under global warming. This may further increase the frequency and intensity of extreme climate events and add uncertainty to the future evolution of ENSO and other climate modes.

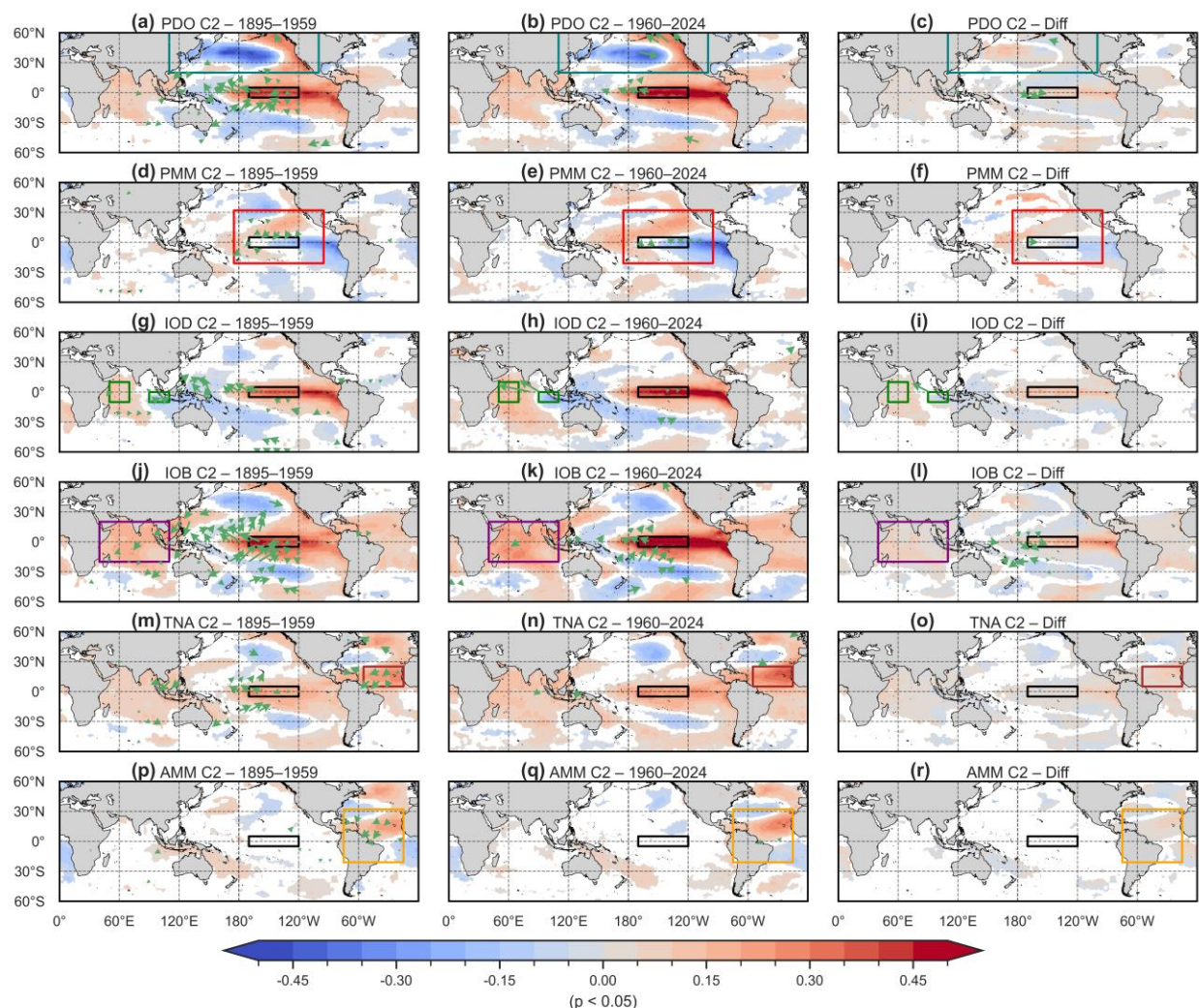


Fig. 6 Changes in the global responses to other climate modes at the interannual time scale before and after global warming ($^{\circ}\text{C s.d.}^{-1}$). Panels (a, d, g, j, m, p) show the spatial response patterns of each climate mode before global warming. Panels (b, e, h, k, n, q) show the corresponding patterns after global warming. Panels (c, f, i, l, o, r) show the differences in the spatial responses (after minus before global warming). The black box marks the Niño 3.4 region, while the other colored boxes indicate the respective domains of each climate mode. Grey shading denotes land areas, the colorbar indicates the magnitude of the SST response, and green arrows denote the wind-field response.

3.5 Effects of Climate Modes on ENSO Predictability under Global Warming

Given that the teleconnections among climate modes in different ocean basins have changed substantially under global warming, this study combines the Niño 3.4 index with climate mode indices from different ocean basins to examine ENSO predictability and to assess how changes in ENSO teleconnections with ocean-basin climate modes under global warming affect ENSO predictability. The results show that ENSO predictability in historical observations is markedly enhanced after global warming (Fig. 7). Before global warming (Fig. 7a), incorporating Pacific climate modes significantly improves one-year-lead ENSO predictability

from 0.16 to 0.23, whereas adding Indian Ocean climate modes increases it only to 0.18. The contribution of Atlantic climate modes to one-year-lead ENSO predictability is relatively small, but at the two-year lead, they improve ENSO predictability from 0.20 to 0.26. After global warming (Fig. 7b), the interactions between ENSO and climate modes in different ocean basins change substantially, and the contribution of these climate modes to ENSO predictability becomes much stronger. The improvements at the one-year and two-year leads increase from 0.11, from 0.16 to 0.27, and 0.07, from 0.20 to 0.27, before warming, to 0.20, from 0.35 to 0.55, and 0.09, from 0.24 to 0.33, after warming, respectively. In particular, the roles of Indian Ocean climate modes, which increase predictability from 0.35 and 0.24 to 0.39 and 0.28, and Atlantic climate modes, which increase predictability from 0.35 and 0.24 to 0.46 and 0.26, become substantially stronger in ENSO prediction. This further confirms the enhanced cross-basin interactions under global warming and is consistent with the conclusions above. After removing the global warming signal in Figs. 6c,d, ENSO predictability weakens slightly, further indicating that the influence of global warming on ENSO and other climate modes is expressed through changes in dynamical mechanisms such as teleconnections. The complex teleconnections between ENSO and these climate modes jointly contribute to the significant increases in ENSO amplitude, frequency, and asymmetry after global warming.

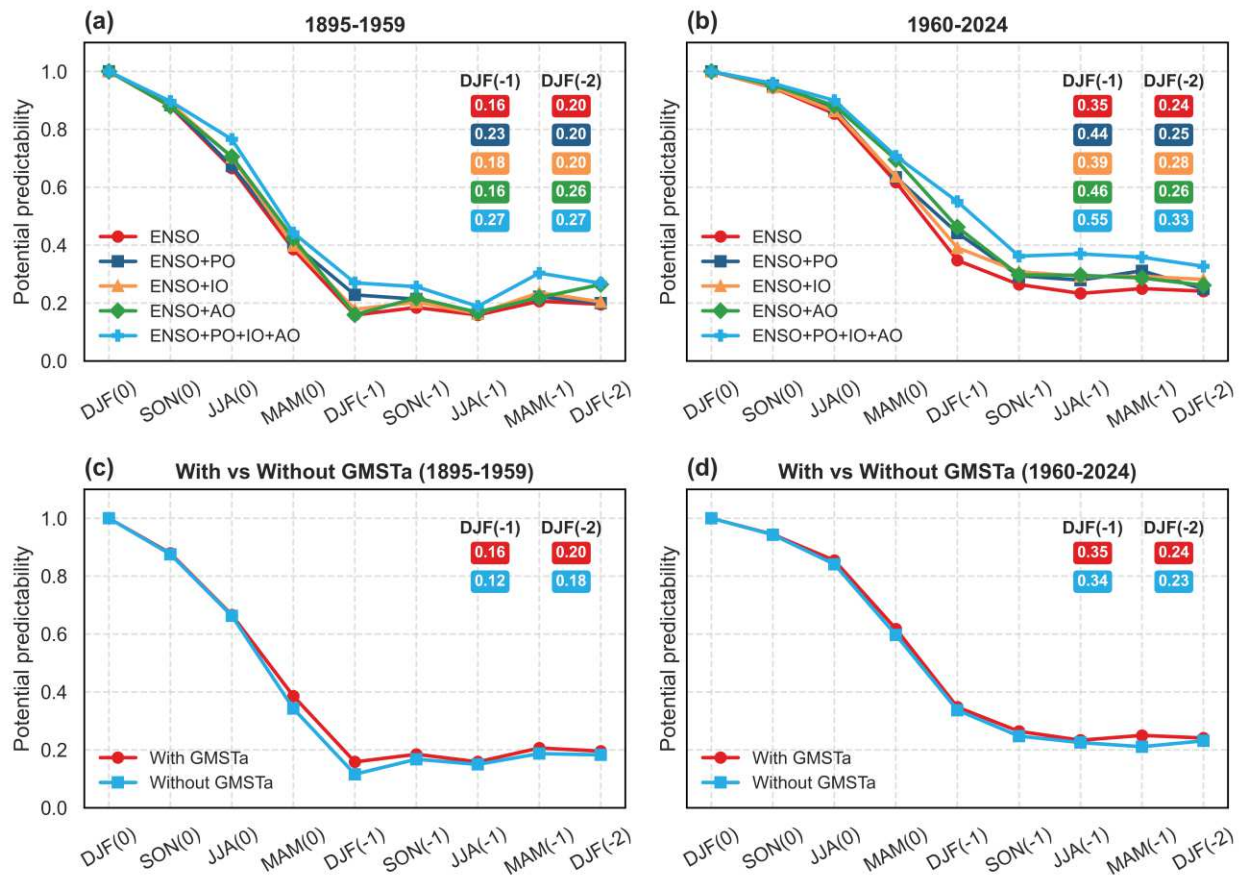


Fig. 7 Changes in ENSO predictability under the influence of global warming. Panels (a, b) show the potential impacts of different climate modes on ENSO predictability before and after global warming. Here, multivariate linear regression is used to quantify the predictive skill of different predictors for winter Niño 3.4. Red circles denote the baseline ENSO predictors,

including GMSTa, Niño1+2, Niño3, Niño4, Niño3.4, and equatorial Pacific HC. Yellow squares add Pacific modes (PDO and PMM) to the baseline predictors, orange triangles add Indian Ocean modes (IOD and IOB), green diamonds add Atlantic modes (TNA and AMM), and blue crosses represent predictions using all predictors combined. Panels (c, d) show the impact of the global warming signal on ENSO predictability; the blue square line indicates results with GMSTa removed. The upper-right corner annotates, in the corresponding colors, the changes in predictability at lead times of one year and two years, respectively.

4 Conclusions

This study investigates changes in the characteristics and interactions of ENSO and cross-basin climate modes under global warming from a multiscale perspective. The results show that global warming not only changes the frequency and intensity of climate modes such as ENSO, but also affects the teleconnections between ENSO and other climate modes, thereby enhancing interactions among climate modes:

(1) After global warming, the intensities of both El Niño and La Niña events show increasing trends, and the frequency of extreme El Niño events increases markedly. ENSO variability increases from 0.75 to 1.25, and its asymmetry increases from 0.25 to 0.38. Meanwhile, the variability of the PMM, IOD, IOBW, TNA, and AMM also increases. Multiscale analysis shows that these modes are dominated by interannual variability and are highly correlated with the global warming signal. After global warming, the PDO amplitude weakens on intra-annual and interannual time scales, whereas the PMM amplitude strengthens on intra-annual, interannual, and decadal time scales. The interannual amplitude and asymmetry of the IOD increase markedly. The IOBW maintains strong oscillations on the intra-annual time scale and shows enhanced cross-basin connections on the interannual time scale. The TNA and AMM exhibit reduced frequencies and enhanced amplitudes across multiple time scales.

(2) The interactions between ENSO and other climate modes are concentrated mainly on the interannual time scale, with the strongest connections occurring between ENSO and the PDO and IOBW, and the weakest connection occurring between ENSO and the AMM. After global warming, the coherent period domain and correlation strength between ENSO and the PDO weaken, and the cold SST response of the PDO over the North Pacific is reduced, leading to a weakened interaction between them. The influence of ENSO on the PMM in winter and spring strengthens, whereas the precursor effect of the PMM on ENSO weakens. ENSO becomes more dominant in its relationship with the IOD, and positive IOD events become more likely to occur. The IOBW remains highly coherent with ENSO and exhibits stronger warm anomaly responses over the central-eastern Pacific and the Atlantic. The precursor effect of the TNA on ENSO is further enhanced, while the connection between the AMM and ENSO, although strengthened to some extent, remains generally weak.

(3) Finally, predictability analyses show that, under the influence of global warming, the impact of cross-basin climate modes on ENSO predictability is enhanced. By incorporating climate modes from different ocean basins into the prediction framework, the improvements in one-year- and two-year-lead ENSO predictability increase from 0.11 and 0.07 before warming to 0.20 and 0.09 after warming, respectively. The contributions from the Indian and Atlantic Ocean modes are particularly evident, suggesting that enhanced cross-basin interactions can provide effective precursor information for ENSO prediction.

Overall, global warming enhances cross-basin teleconnections and promotes increases in ENSO amplitude, frequency, and asymmetry. This study provides an important basis for understanding the future evolution of ENSO and improving its prediction.

Author Contributions Bingkun Wang performed the formal analysis, developed the methodology, implemented the software, conducted data processing and visualization, interpreted the results, and wrote the original draft. Zhiping Chen contributed to the conceptualization of the study, methodology development, supervision, original draft and manuscript review and editing. Zhuo Liu, Yongkang Sun, Yu Gao, and Tieding Lu contributed to the interpretation and discussion of the results and reviewed and edited the manuscript. All authors read and approved the final manuscript.

Funding This research was supported by the Outstanding Youth Foundation Project of the Jiangxi Provincial Natural Science Foundation (Grant No. 20242BAB22001) and the National Natural Science Foundation of China (Grant Nos. 42374040 and 41904031).

Data Availability The HadISST sea surface temperature dataset is available from the Met Office Hadley Centre (<https://www.metoffice.gov.uk/hadobs/hadisst/>). The HadCRUT5 surface temperature dataset is available from the Met Office Hadley Centre (<https://www.metoffice.gov.uk/hadobs/hadcrut5/>). The Twentieth Century Reanalysis wind-field data (20CRv3) are available from the NOAA Physical Sciences Laboratory (https://psl.noaa.gov/data/gridded/data.20thC_ReanV3.html). The ERA5 high-resolution reanalysis wind-field data are provided by ECMWF (<https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=download>). The PSL climate mode indices, including Niño 3.4, PDO, PMM, IOD, TNA, and AMM, are available from the NOAA Physical Sciences Laboratory (<https://psl.noaa.gov/data/timeseries/month/>).

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

References

Cai W, Ng B, Geng T, et al (2023) Anthropogenic impacts on twentieth-century ENSO variability changes. *Nat Rev Earth Environ* 4:407–418. <https://doi.org/10.1038/s43017-023-00427-8>

609 Cai W, Ng B, Wang G, et al (2022) Increased ENSO sea surface temperature variability under four IPCC emission
610 scenarios. *Nat Clim Change* 12:228–231. <https://doi.org/10.1038/s41558-022-01282-z>

611 Cai W, Santoso A, Collins M, et al (2021) Changing el niño–southern oscillation in a warming climate. *Nat Rev*
612 *Earth Environ* 2:628–644. <https://doi.org/10.1038/s43017-021-00199-z>

613 Cai W, Wu L, Lengaigne M, et al (2019) Pantropical climate interactions. *Science* 363:eaav4236.
614 <https://doi.org/10.1126/science.aav4236>

615 Chang P, Ji L, Li H (1997) A decadal climate variation in the tropical atlantic ocean from thermodynamic air-sea
616 interactions. *Nature* 385:516–518. <https://doi.org/10.1038/385516a0>

617 Chen H, Jin Y, Liu Z, et al (2024a) Central-pacific el niño-southern oscillation less predictable under greenhouse
618 warming. *Nat Commun* 15:4370. <https://doi.org/10.1038/s41467-024-48804-1>

619 Chen H-C, Jin F-F, Jiang L (2021) The phase-locking of tropical north atlantic and the contribution of ENSO.
620 *Geophys Res Lett* 48:e2021GL095610. <https://doi.org/10.1029/2021GL095610>

621 Chen S, Chen W, Xie S-P, et al (2024b) Strengthened impact of boreal winter north pacific oscillation on ENSO
622 development in warming climate. *npj Clim Atmos Sci* 7:69–88. [https://doi.org/10.1038/s41612-024-00615-](https://doi.org/10.1038/s41612-024-00615-3)
623 [3](https://doi.org/10.1038/s41612-024-00615-3)

624 Chen Z, Li L, Wang B, et al (2024c) The impact of global warming on ENSO from the perspective of objective
625 signals. *Atmos Res* 299:107176. <https://doi.org/10.1016/j.atmosres.2023.107176>

626 Di Lorenzo E, Xu T, Zhao Y, et al (2023) Modes and mechanisms of pacific decadal-scale variability. *Annu Rev*
627 *Mar Sci* 15:249–275. <https://doi.org/10.1146/annurev-marine-040422-084555>

628 Enfield DB, Mestas-Núñez AM, Mayer DA, Cid-Serrano L (1999) How ubiquitous is the dipole relationship in
629 tropical atlantic sea surface temperatures? *J Geophys Res: Oceans* 104:7841–7848.
630 <https://doi.org/10.1029/1998JC900109>

631 Fan H, Huang B, Yang S, Dong W (2021) Influence of the pacific meridional mode on ENSO evolution and
632 predictability: asymmetric modulation and ocean preconditioning. *J Clim* 34:1881–1901.
633 <https://doi.org/10.1175/JCLI-D-20-0109.1>

634 Fan H, Wang C, Yang S (2023) Asymmetry between positive and negative phases of the pacific meridional mode: a
635 contributor to ENSO transition complexity. *Geophys Res Lett* 50:e2023GL104000.
636 <https://doi.org/10.1029/2023GL104000>

637 Fan H, Yang S, Wang C, et al (2022) Strengthening amplitude and impact of the pacific meridional mode on ENSO
638 in the warming climate depicted by CMIP6 models. *J Clim* 35:5195–5213. [https://doi.org/10.1175/JCLI-D-](https://doi.org/10.1175/JCLI-D-21-0683.1)
639 [21-0683.1](https://doi.org/10.1175/JCLI-D-21-0683.1)

640 Fang S-W, Yu J-Y (2020) A control of ENSO transition complexity by tropical pacific mean SSTs through tropical-
641 subtropical interaction. *Geophys Res Lett* 47:e2020GL087933. <https://doi.org/10.1029/2020GL087933>

642 Geng T, Jia F, Cai W, et al (2023) Increased occurrences of consecutive la niña events under global warming.
643 *Nature* 619:774–781. <https://doi.org/10.1038/s41586-023-06236-9>

644 Geng T, Yang Y, Wu L (2019) On the mechanisms of pacific decadal oscillation modulation in a warming climate. *J*
645 *Clim* 32:1443–1459. <https://doi.org/10.1175/JCLI-D-18-0337.1>

646 Ham Y-G, Kug J-S, Park J-Y, Jin F-F (2013) Sea surface temperature in the north tropical atlantic as a trigger for el
647 niño/southern oscillation events. *Nat Geosci* 6:112–116. <https://doi.org/10.1038/ngeo1686>

648 Hu A, Richter I, Okumura Y, et al (2025) Unraveling the complexity of global climate dynamics: interactions
649 among el niño–southern oscillation, atlantic meridional overturning circulation, and tropical basins across
650 different timescales. *Ocean-Land-Atmos Res* 4:0096. <https://doi.org/10.34133/olar.0096>

651 Huang NE, Shen Z, Long SR, et al (1998) The empirical mode decomposition and the hilbert spectrum for nonlinear
652 and non-stationary time series analysis. *Proc R Soc Lond, A: Math Phys Eng Sci* 454:903–995.
653 <https://doi.org/10.1098/rspa.1998.0193>

654 Huang NE, Wu Z (2008) A review on hilbert-huang transform: method and its applications to geophysical studies.
655 *Rev Geophys* 46:2007RG000228. <https://doi.org/10.1029/2007RG000228>

656 Izumo T, Vialard J, Lengaigne M, et al (2010) Influence of the state of the Indian Ocean dipole on the following
657 year's el niño. *Nat Geosci* 3:168–172. <https://doi.org/10.1038/ngeo760>

658 Jin Y, Meng X, Zhang L, et al (2023) The Indian Ocean weakens the ENSO spring predictability barrier: role of the
659 Indian Ocean basin and dipole modes. *J Clim* 36:8331–8345. <https://doi.org/10.1175/JCLI-D-22-0800.1>

660 Jo H-S, Ham Y-G, Kug J-S, et al (2022) Southern Indian Ocean dipole as a trigger for central pacific el niño since
661 the 2000s. *Nat Commun* 13:6965. <https://doi.org/10.1038/s41467-022-34721-8>

662 Li S, Wu L, Yang Y, et al (2020) The pacific decadal oscillation less predictable under greenhouse warming. *Nat*
663 *Clim Change* 10:30–34. <https://doi.org/10.1038/s41558-019-0663-x>

664 Liang L, Ziegler AD, Chen D, et al (2024) Changing footprint of the pacific decadal oscillation on global land
665 surface air temperature. *Sci Bull* 69:445–448. <https://doi.org/10.1016/j.scib.2023.12.004>

666 Liu B, Gan B, Jia F, Wu L (2024) Impact of the north pacific meridional mode on the tropical pacific modulated by
667 the interdecadal pacific oscillation. *J Clim* 37:2199–2216. <https://doi.org/10.1175/JCLI-D-23-0448.1>

668 Mandal S, Yuvaraj S, Mazumdar J, Ballav J (2024) Analyzing the rainfall trend and hydroclimatic teleconnections
669 using hilbert huang transform for the coastal smart cities of India. *Urban Clim* 58:102204.
670 <https://doi.org/10.1016/j.uclim.2024.102204>

671 Mandic DP, Rehman NU, Wu Z, Huang NE (2013) Empirical mode decomposition-based time-frequency analysis
672 of multivariate signals: the power of adaptive data analysis. *IEEE Signal Process Mag* 30:74–86.
673 <https://doi.org/10.1109/MSP.2013.2267931>

674 Newman M, Alexander MA, Ault TR, et al (2016) The pacific decadal oscillation, revisited. *J Clim* 29:4399–4427.
675 <https://doi.org/10.1175/JCLI-D-15-0508.1>

676 Park J-H, Kug J-S, Yang Y-M, et al (2023) Distinct decadal modulation of atlantic-niño influence on ENSO. *npj*
677 *Clim Atmos Sci* 6:105. <https://doi.org/10.1038/s41612-023-00429-9>

678 Power S, Lengaigne M, Capotondi A, et al (2021) Decadal climate variability in the tropical pacific: characteristics,
679 causes, predictability, and prospects. *Science* 374:eaay9165. <https://doi.org/10.1126/science.aay9165>

680 Rayner NA, Parker DE, Horton EB, et al (2003) Global analyses of sea surface temperature, sea ice, and night
681 marine air temperature since the late nineteenth century. *J Geophys Res: Atmos* 108:2002JD002670.
682 <https://doi.org/10.1029/2002JD002670>

683 Ren H-L, Jin F-F (2013) Recharge oscillator mechanisms in two types of ENSO. *J Clim* 26:6506–6523.
684 <https://doi.org/10.1175/JCLI-D-12-00601.1>

685 Saji NH, Goswami BN, Vinayachandran PN, Yamagata T (1999) A dipole mode in the tropical indian ocean. *Nature*
686 401:361–363. <https://doi.org/10.1038/43854>

687 Sharma S, Ha K-J, Yamaguchi R, et al (2023) Future indian ocean warming patterns. *Nat Commun* 14:1789.
688 <https://doi.org/10.1038/s41467-023-37435-7>

689 Sun Q, Zhao H, Klotzbach PJ, et al (2024) Strengthened combined impact of the pacific and atlantic meridional
690 modes on eastern north pacific tropical cyclones since the 1990s. *J Clim* 37:3345–3357.
691 <https://doi.org/10.1175/JCLI-D-23-0582.1>

692 Tao L, Xiao Y, Zhao J (2024) Relationship between the pacific meridional mode and el niño–southern oscillation on
693 different timescales. *Atmos Res* 302:107309. <https://doi.org/10.1016/j.atmosres.2024.107309>

694 Timmermann A, An S-I, Kug J-S, et al (2018) El niño–southern oscillation complexity. *Nature* 559:535–545.
695 <https://doi.org/10.1038/s41586-018-0252-6>

696 Wang R, He J, Luo J-J, Chen L (2024) Atlantic warming enhances the influence of atlantic niño on ENSO. *Geophys*
697 *Res Lett* 51:e2023GL108013. <https://doi.org/10.1029/2023GL108013>

698 Wu J, Fan H, Lin S, et al (2024) Boosting effect of strong western pole of the Indian Ocean dipole on the decay of el
699 niño events. *npj Clim Atmos Sci* 7:6. <https://doi.org/10.1038/s41612-023-00554-5>

700 Yeh S-W, Cai W, Min S-K, et al (2018) ENSO atmospheric teleconnections and their response to greenhouse gas
701 forcing. *Rev Geophys* 56:185–206. <https://doi.org/10.1002/2017RG000568>

702 Zhang L, Delworth TL (2016) Simulated response of the pacific decadal oscillation to climate change. *J Clim*
703 29:5999–6018. <https://doi.org/10.1175/JCLI-D-15-0690.1>

704 Zhang L, Wang G, Newman M, Han W (2021) Interannual to decadal variability of tropical indian ocean sea surface
705 temperature: pacific influence versus local internal variability. *J Clim* 34:2669–2684.
706 <https://doi.org/10.1175/JCLI-D-20-0807.1>

707 Zhao Y, Jin Y, Capotondi A, et al (2023) The role of tropical atlantic in ENSO predictability barrier. *Geophys Res*
708 *Lett* 50:e2022GL101853. <https://doi.org/10.1029/2022GL101853>

709 Zhao Y, Song F, Sun D, et al (2025) Different roles of Indian Ocean basin and dipole modes in tropical pacific
710 climate variability. *npj Clim Atmos Sci* 8:163. <https://doi.org/10.1038/s41612-025-01065-1>

711 Zheng Y, Chen S, Chen W, Yu B (2023) A continuing increase of the impact of the spring north pacific meridional
712 mode on the following winter el niño and southern oscillation. *J Clim* 36:585–602.
713 <https://doi.org/10.1175/JCLI-D-22-0190.1>