

A trans-hemispheric relay of extratropical forcing governs ENSO evolution

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Abstract

The decay of El Niño–Southern Oscillation (ENSO) events exhibits pronounced diversity, ranging from rapid termination to multi-year persistence. Using reanalysis datasets and a long CESM1 preindustrial control simulation, we show that this diversity arises from a seasonally coordinated relay between Northern and Southern Hemisphere extratropical atmospheric forcing. Shortly after the boreal-winter ENSO peak, Northern Hemisphere forcing sets the initial decay pace. This pace determines whether sea-surface temperature anomalies in the central equatorial Pacific persist into boreal summer of the decay year, when they can initiate Southern Hemisphere extratropical variability. Southern Hemisphere forcing then becomes dominant and determines whether ENSO reverses phase, producing a single-year event, or persists and reintensifies into a multi-year event. Removing ENSO-related signals reveals that this Northern Hemisphere–to–tropical central Pacific–to–Southern Hemisphere sequence remains evident, indicating an ENSO-independent hemispheric relay mode of extratropical forcing. ENSO decay diversity can therefore be understood within a two-component framework: a canonical tropical Pacific-dominated decay tendency that provides the backbone ENSO evolution, and an ENSO-independent hemispheric relay mode of extratropical Pacific influence that determines whether anomalies persist or reverse in the following year.

Main

El Niño–Southern Oscillation (ENSO) events can follow markedly different decay pathways after their winter peak, ranging from rapid termination to multi-year persistence. Classical theories of ENSO dynamics, such as the recharge–discharge oscillator framework, explain ENSO growth and decay primarily through coupled ocean–atmosphere interactions within the tropical Pacific. Within this framework, ENSO evolution is governed largely by equatorial heat content recharge–discharge processes and associated air–sea feedbacks ^{1–4}. Yet this tropical framework does not fully explain the observed diversity of ENSO decay pathways. In recent decades, multi-year (MY) ENSO events—including the 2020–2023 triple-dip La Niña and the reintensified 2014–2016 El Niño—have occurred more frequently, challenging the view of ENSO as a predominantly single-year (SY) phenomenon. Compared with SY events, MY ENSO episodes tend to prolong and amplify climate anomalies across multiple regions ^{5–9}, underscoring the importance of understanding the processes that govern ENSO decay and post-peak evolution.

Increasing attention has been directed toward the role of extratropical processes in shaping ENSO diversity. Studies motivated by the identification of central-Pacific ENSO events have highlighted the influence of North Pacific atmospheric variability ¹⁰, often characterized by the North Pacific Oscillation (NPO), which can generate subtropical sea-surface temperature (SST) footprints that extend into the equatorial Pacific through wind–evaporation–SST (WES) feedback ^{11–15}. These extratropical perturbations can interact with tropical air–sea coupling and thereby influence ENSO spatial structure and evolution, complementing conventional tropical mechanisms.

Extratropical influences have also been linked to differences in ENSO temporal evolution. Variability over the North Pacific can modulate subtropical trade winds and induce SST anomalies (SSTAs) associated with the North Pacific Meridional Mode (NPMM), which may extend equatorward and persist into the ENSO decay phase^{16–20}. In parallel, variability over the South Pacific, often characterized by the Southern Pacific Oscillation (SPO), can influence tropical Pacific conditions through analogous subtropical–tropical coupling processes, thereby modulating ENSO evolution during its decay and post-peak stages^{21,22}. Together, these findings suggest that extratropical forcing can affect not only the structure but also the temporal evolution of ENSO, pointing to a potential role of forcings from both hemispheres.

The distinct seasonal preferences of Northern and Southern Hemisphere modes, with North Pacific variability peaking in boreal winter²³ and South Pacific variability peaking in boreal summer²⁴, raise the possibility that extratropical forcing from the two hemispheres may be dynamically linked and coordinated to influence ENSO evolution. Establishing this possibility and its role is essential for understanding ENSO decay diversity.

Here, we analyze observational datasets and climate model simulations to identify a seasonally evolving process that connects extratropical variability in both hemispheres and shapes ENSO decay pathways. This process is manifested as a trans-hemispheric relay of extratropical forcing, in which Northern Hemisphere variability regulates the early decay pace and establishes a central-Pacific SST footprint that subsequently enables Southern Hemisphere variability to determine whether ENSO persists or reverses. This relay represents an ENSO-independent mode of variability that acts as a fundamental driver of ENSO evolution, complementing the canonical tropical processes that govern ENSO development and decay.

Extratropical control of ENSO decay pathways

We first apply an extended empirical orthogonal function (EEOF) analysis to SSTAs during 1940–2024 to identify the dominant spatiotemporal patterns of ENSO evolution from the mature boreal winter through the following year (see Methods). The two leading modes explain 33.49% and 23.97% of the total variance (Fig. 1) and represent the primary evolution pathways contributing to ENSO decay diversity. SSTAs regressed onto the principal component of the first mode (PC1) depict a phase-maintenance pathway in which warm anomalies decay slowly and reintensify in subsequent seasons, leading to MY ENSO events (Figs. 1a–e). In contrast, SSTAs regressed onto the second mode (PC2) describe a phase-transition pathway in which warm anomalies weaken after D(0)JF(1), reverse sign by JJA(1), and evolve into La Niña by D(1)JF(2), resulting in SY ENSO events (Figs. 1f–j).

To identify the processes underlying these pathways, we examine the associated 850-hPa wind anomalies (Fig. 1). The regression patterns reveal a two-stage influence of extratropical circulation on ENSO decay. Northern Hemisphere variability dominates during the immediate post-peak stage from

D(0)JF(1) to MAM(1), whereas Southern Hemisphere variability emerges in MAM(1), strengthens in JJA(1), and persists through the subsequent autumn and winter.

During the immediate post-peak stage, the circulation differences between the two pathways exhibit a clear North Pacific Oscillation (NPO)-like structure over the North Pacific (Figs. 1k–l). In the phase-maintenance pathway (EEOF1), an atmospheric circulation anomaly over the North Pacific, superimposed onto a positive NPO phase, features a southward-extended cyclonic anomaly, which weakens the background trade winds and favors the persistence of central-Pacific SSTAs, contributing to slower ENSO decay^{20,25}. In contrast, the opposite NPO phase in EEOF2 strengthens the trade winds and promotes rapid cooling of the equatorial Pacific, accelerating ENSO termination and phase reversal. These results indicate that Northern Hemisphere extratropical variability plays a key role in regulating ENSO evolution during the early post-peak stage.

During the late-decay stage, Southern Hemisphere extratropical variability becomes increasingly important. The circulation differences between the two pathways reveal an emerging SPO-like dipole over the South Pacific (Fig. 1l). In EEOF1, a positive SPO phase favors equatorial westerly anomalies and associated oceanic adjustment that sustains warm SSTAs into the second year (Fig. 1b–e). In contrast, a negative SPO phase promotes equatorial easterlies and upwelling Kelvin waves, accelerating the transition toward La Niña (Fig. 1h–j)^{21,26}.

Overall, these results reveal seasonally alternating extratropical influences on ENSO decay. Northern Hemisphere forcing regulates ENSO evolution during the immediate post-peak stage, whereas Southern Hemisphere forcing determines whether ENSO anomalies persist or transition in later seasons. This seasonally connected hemispheric relay of NPO and SPO signals is illustrated in Fig. 1p, showing a transition in early boreal spring from dominant NPO variability to increasing SPO influence.

Hemispheric relay revealed by SY and MY ENSO events

To further examine the hemispheric relay suggested above, we analyze SY and MY ENSO events in a 2,200-year CESM1 preindustrial control simulation, which provides a much larger event sample than observations. Applying the same EEOF analysis reproduces the two ENSO decay pathways identified in observations (Extended Data Fig. 1), and composites of SY and MY events confirm the seasonally alternating influences of Northern and Southern Hemisphere extratropical forcing (Extended Data Figs. 2–3). We then examine how Northern Hemisphere forcing during the ENSO mature winter becomes linked to Southern Hemisphere variability in subsequent seasons. Specifically, we assess whether this hemispheric relay is modulated by ENSO amplitude or zonal structure, represented by the Niño 3.4 index and the zonal location (ZL) index, respectively. Because these relationships may differ between ENSO phases, El Niño and La Niña events are analyzed separately.

For El Niño events, MY and SY cases exhibit comparable Niño 3.4 amplitudes from the developing summer through the mature winter [D(0)JF(1)] (Fig. 2a), indicating that differences in subsequent evolution do not arise from ENSO intensity. Instead, the two groups diverge in ENSO zonal structure

during the immediate post-peak stage. MY El Niño events display a westward-shifted SST center (negative ZL index), whereas SY events exhibit a more eastward-centered warming pattern (Fig. 2b). Because westward-displaced tropical SSTAs more effectively excite North Pacific variability^{27,28}, MY events are accompanied by stronger NPO variability during winter and early spring (Fig. 2c), followed by the development of a pronounced NPMM during spring (Extended Data Fig. 4a). Consistent with this extratropical–tropical interaction, MY events exhibit a slower springtime decay of Niño 3.4 compared with SY events.

As the seasonal cycle progresses into the late-decay stage, Northern Hemisphere differences weaken, while Southern Hemisphere variability diverges sharply. MY and SY El Niño events exhibit opposite-signed SPO anomalies that peak during JJAS(1) (Fig. 2d), accompanied by a clear separation in the SPMM index (Extended Data Fig. 4b). These Southern Hemisphere signals coincide with contrasting ENSO outcomes: MY El Niño events transition from slow spring decay to reintensification during summer and autumn, whereas SY events continue a monotonic decay toward termination (Fig. 2a).

La Niña evolution largely mirrors the El Niño case with opposite polarity, indicating that the same hemispheric relay operates across ENSO phases. Relative to SY events, MY La Niña events feature stronger negative NPO variability and a more pronounced negative NPMM during boreal winter to early spring (Fig. 2g and Extended Data Fig. 4c), followed by stronger negative SPO anomalies peaking in JJAS(1) and a more pronounced negative SPMM during summer–autumn of Year (1) (Fig. 2h and Extended Data Fig. 4d).

These index analyses indicate that persistent central-Pacific SSTAs (typically represented by the Niño 4 SSTAs) during the immediate post-peak stage are a defining feature of MY ENSO evolution. These anomalies arise from Northern Hemisphere extratropical forcing during the post-peak stage of ENSO evolution and subsequently excite Southern Hemisphere variability during the late-decay stage. This cross-seasonal linkage between Northern Hemisphere forcing, tropical central-Pacific SSTAs, and Southern Hemisphere variability is further confirmed by the statistically significant correlations (99% confidence level) shown in Extended Data Fig. 5. These correlations link the wintertime [D(0)JFM(1)] Northern Hemisphere extratropical NPO index in the first year of ENSO, to springtime [MAM(1)] tropical central-Pacific Niño 4 SST index in the decaying year, then to the summertime [JJAS(1)] Southern Hemisphere extratropical SPO index, and finally to the second-winter [D(1)JF(2)] Niño 3.4 index. Within this sequence, MAM(1) Niño 4 SSTAs serve as a key intermediary, linking wintertime NPO variability to summertime SPO variability and thereby helping determine whether ENSO persists or reverses phase in the second year. Therefore, ENSO zonal structure, rather than ENSO amplitude, acts as the handover mechanism linking Northern and Southern Hemisphere extratropical influences.

To further examine whether the hemispheric relay inferred from the composites operates systematically across ENSO events, we analyze the joint distribution of boreal-winter NPO [D(0)JFM(1)] and boreal-summer SPO [JJAS(1)] in the CESM1 simulation (Fig. 3). For El Niño events (Fig. 3a), MY cases cluster preferentially in the quadrant characterized by simultaneously positive NPO and positive SPO, whereas

SY events are more broadly distributed and largely avoid this quadrant. Quantitatively, configurations with both NPO and SPO exceeding +0.5 standard deviations account for 40.9% of MY El Niño events but only 1.1% of SY events, while cases lacking strong extratropical signals dominate the SY population (63.3%) but are rare among MY events (10.7%, Fig. 3b). These results indicate that MY El Niño events preferentially occur when wintertime NPO and summertime SPO are both strong and of the same sign, consistent with a seasonally connected hemispheric relay mechanism.

For La Niña (Fig. 3d), a nearly mirrored structure emerges: MY events preferentially occur under concurrently negative NPO in boreal winter followed by a negative SPO in the subsequent boreal summer, with such configurations accounting for 43.9% of cases. In contrast, SY La Niña events are dominated by weak or uncoordinated extratropical forcing (60.8%, Fig. 3e). These results further demonstrate that coordinated extratropical variability from both hemispheres is a defining feature of MY ENSO evolution, irrespective of ENSO phase.

Building on this distributional evidence, we quantify how different NPO–SPO configurations influence the likelihood of MY ENSO evolution (Figs. 3c, f). For El Niño events, when both the D(0)JFM(1) NPO and JJAS(1) SPO exceed +0.5 standard deviations, 97.1% of cases evolve into MY events—much higher than when only NPO is strong (36.4%), only SPO is strong (70.7%), or neither signal is strong (11.9%) (Fig. 3c). A similar result holds for La Niña events: when both NPO and SPO fall below −0.5 standard deviations, 94.6% of cases correspond to MY events (Fig. 3f). These statistics demonstrate that a hemispheric relay involving coherent NPO and SPO variability strongly favors MY ENSO evolution.

Importantly, the conditional probabilities reveal an asymmetry in the relative influence of the two extratropical signals. Across both ENSO phases, strong SPO variability alone is more predictive of MY evolution than strong NPO variability alone (70.7% versus 36.4% for El Niño and 74.7% versus 54.2% for La Niña; Figs. 3c, f). This result indicates that Southern Hemisphere extratropical forcing plays the dominant role in determining whether ENSO SSTAs persist or reverse in the second year, whereas Northern Hemisphere forcing primarily preconditions the evolution by regulating the decay pace and sustaining central-Pacific SSTAs.

Taken together, the CESM1 composites and event statistics reveal a seasonally connected hemispheric relay mechanism underlying MY ENSO evolution. Wintertime NPO forcing sustains central-Pacific SSTAs into boreal spring, thereby establishing a tropical SST footprint that promotes the development of summertime SPO variability. The ensuing Southern Hemisphere forcing then plays a dominant role in determining whether ENSO anomalies persist into, or reverse during, the second year.

ENSO-independent hemispheric relay mode

The results from the previous sections indicate that ENSO evolution is shaped by a Northern Hemisphere–to–tropical central Pacific–to–Southern Hemisphere relay of extratropical forcing. As shown in the previous analyses, the relay can operate as a self-sustained linkage that may not require the presence of ENSO forcing. This raises the possibility that the hemispheric relay of extratropical

forcing may be ENSO-independent and represent a previously unrecognized mode of cross-hemispheric variability.

To examine this possibility, we remove the linear influence of mature-phase ENSO SSTAs from the two EEOF modes. Specifically, the component of PC1 and PC2 linearly associated with the D(0)JF(1) cold tongue index (CTI) is removed, and the residual PCs (denoted PC1_res and PC2_res) are used in partial regression analyses of atmospheric circulation and SSTAs. Remarkably, after removing ENSO influences (Figs. 4a–j), the two ENSO decay pathways (EEOF1 and EEOF2) exhibit nearly mirror-image evolutions in both tropical SSTAs and extratropical atmospheric circulation, representing the positive and negative phases of a hemispheric relay process.

During D(0)JF(1), the residual circulation over the North Pacific already shows two sharply contrasting extratropical states. In the PC1_res regression, a prominent anomalous cyclone is accompanied by westerly and southwesterly wind anomalies extending from the subtropical northeastern Pacific toward the western Pacific, together with a positive NPMM pattern (Fig. 4a). In contrast, the PC2_res regression exhibits an anomalous anticyclone accompanied by northeasterly wind anomalies over the subtropical North Pacific and an opposite-signed SST footprint, producing a negative NPMM pattern (Fig. 4f). As the seasonal cycle advances into boreal spring, these ENSO-independent North Pacific circulation and SSTAs intensify and extend equatorward through WES feedback, imprinting opposite-signed anomalies onto the tropical central Pacific (Figs. 4b, g). The resulting SST footprint then serves as an effective intermediary, leading to the emergence of opposite-phased SPO anomalies over the South Pacific from boreal spring into summer (Figs. 4c, h).

This indicates that the two ENSO evolution pathways arise from opposite phases of a hemispheric relay mode of extratropical forcing. This interpretation is further supported by the strong anti-correlation ($r = -0.91$ over 1854–2024; Fig. 4p) between the two residual PCs. In its positive phase—characterized by a positive NPO followed by a positive SPO—ENSO events preferentially evolve along the phase-maintenance pathway (EEOF1), favoring MY evolution. In its negative phase, events more often follow the phase-transition pathway (EEOF2), leading to SY events. Consistent with this interpretation, PC1_res and PC2_res are tightly linked to the subsequent-year Niño 3.4 state with correlation coefficients of 0.88 and -0.92 over 1854–2024, respectively.

The persistence of coherent but oppositely phased NPO signals after removing ENSO forcing suggests that the initial NPO anomalies, in addition to being ENSO-forced, may also originate from intrinsic atmospheric variability or remote SSTAs outside the tropical Pacific. Regardless of their origin, once established, these Northern Hemisphere extratropical perturbations interact with the tropical Pacific and are subsequently relayed to the Southern Hemisphere, forming a seasonally connected sequence of extratropical–tropical–extratropical interactions that can interact with conventional tropical ENSO dynamics (e.g., the recharge–discharge process in the tropical Pacific) to produce the phase-maintenance and phase-transition pathways of ENSO decay.

Additional support for the existence of this ENSO-independent hemispheric relay mode is obtained from an EEOF analysis of sea-level pressure (SLP) over the Pacific sector (35°S–35°N, 135°E–80°W) after removing its linear ENSO-related component. The leading EEOF mode exhibits a clear trans-hemispheric transition structure (Figs. 4k–o), and regressions of winds and SSTAs onto its PC1 reproduce the key circulation–SST features of the hemispheric relay. This coherent trans-hemispheric evolution therefore represents an ENSO-independent hemispheric relay mode.

Conclusions

A central result of this study is that ENSO decay is governed by two temporally distinct yet dynamically connected stages. Northern Hemisphere extratropical forcing modulates the early post-peak decay pace and imprints an SST footprint that extends from the subtropical North Pacific into the tropical western Pacific. This footprint—captured by Niño 4–like anomalies in boreal spring—acts as a key intermediary enabling the emergence of summertime South Pacific variability. Once established, Southern Hemisphere forcing modulates equatorial winds and the associated oceanic adjustment, favoring either phase persistence or phase reversal. This seasonally connected hemispheric relay is schematically summarized in Fig. 5 and highlights how extratropical influences from the two hemispheres are dynamically linked in shaping ENSO evolution.

Further analysis reveals that the Northern Hemisphere–to–tropical central Pacific–to–Southern Hemisphere relay is largely independent of the canonical ENSO dynamics operating in the tropical Pacific. After removing the ENSO-related SST signal, the hemispheric relay remains evident, indicating that it represents a distinct dynamical process rather than a passive response to ENSO forcing. This relay therefore acts as an external modulation of the canonical tropical ENSO decay process.

Taken together, these results suggest that ENSO decay diversity can be understood within a two-component framework. One component reflects the canonical, primarily zonal decay tendency governed by tropical coupled dynamics, which provides the backbone evolution following the ENSO peak. Superimposed on this tendency is an ENSO-independent, trans-hemispheric relay of extratropical forcing that modulates the post-peak trajectory. Through this relay, Northern Hemisphere variability first preconditions the tropical Pacific during the early decay stage, while Southern Hemisphere variability subsequently determines whether ENSO anomalies persist into a second year or reverse phase.

Several uncertainties and limitations merit consideration. Although the hemispheric relay appears robust in both observations and long coupled simulations, its representation may depend on model fidelity in simulating extratropical–tropical coupling and associated air–sea feedbacks. In addition, while the NPO and SPO contain substantial internal atmospheric variability, their variability may also be influenced by SSTAs in other ocean basins, making it difficult to fully isolate their independent contributions. Moreover, the impacts of extratropical forcing on ENSO decay are realized through interactions with tropical Pacific SSTAs, indicating that the relay operates in conjunction with, rather than independently of, tropical coupled processes. These considerations suggest that uncertainties remain in quantifying the relative

contributions of extratropical forcing and tropical dynamics, and how their interplay may change under different climate states remains an open question.

In summary, this study identifies, for the first time, the existence of a hemispheric relay mode of extratropical forcing. While we emphasize in this study its role in ENSO evolution, it may also represent a previously unrecognized mechanism through which climate variability in one hemisphere becomes synchronized with that in the other. This hemispheric relay mode may have broader implications for climate dynamics, such as influencing the pace and structure of global climate variability and change by dynamically linking the two hemispheres. Future studies are needed to examine whether this hemispheric relay mode exhibits a preferred periodicity and to better understand its role under changing climate conditions.

Methods

Datasets

The monthly mean SST data used in this study are obtained from the Extended Reconstructed SST dataset, version 5 (ERSST.v5) ²⁹. Atmospheric circulation fields are taken from the ERA5 reanalysis for the period 1940–2024, including SLP, latent heat flux, and lower-level circulation variables. Interannual variability signals were extracted by removing the linear trend, the annual cycle, and a 13-year running mean from the original datasets.

To increase the sample size of MY ENSO events beyond what is available in observations, we additionally analyze years 400–2200 of a 2,200-year preindustrial control simulation from the Community Earth System Model, version 1 (CESM1) ³⁰. CESM1 has been extensively used for ENSO research because it reproduces many observed features of ENSO with comparatively high fidelity among contemporary coupled models, including event frequency, amplitude, spatial structure, temporal evolution, and overall diversity ^{31,32}. In particular, CESM1 has been shown to capture key contrasts between SY and MY ENSO events that resemble those found in observations ^{18,33–35}. Following these studies, anomalies are computed by first removing linear trends and a 13-year running mean, and then subtracting the climatological seasonal cycle from each field.

ENSO events were identified using the same criteria as for observations, based on ± 0.5 standard deviations of the Niño 3.4 index during the first winter [D(0)JF(1)]. A total of 353 El Niño and 384 La Niña events were identified over the 1800-year analysis period.

Indices

To characterize ENSO amplitude and structure, we use several Niño indices, defined as area-mean SSTAs over the tropical Pacific: Niño 3.4 index (5°S–5°N, 170°–120°W), Niño 4 index (5°S–5°N, 160°E–150°W), Niño 3 index (5°S–5°N, 90–150°W) and CTI (6°S–6°N, 180°–90°W). To describe ENSO zonal

structure, we define a ZL index as the difference between the Niño 3 index and Niño 4 index ($ZL = \text{Niño 3} - \text{Niño 4}$).

The NPO represents a north–south seesaw mode of SLP variations over the North Pacific and its index is defined by the PC corresponding to the second empirical orthogonal function (EOF) mode of normalized SLP anomalies over the North Pacific (20° – 85° N, 120° E– 120° W)^{26,36}. While the SPO is a Southern Hemisphere counterpart of the NPO, and its index is defined as the PC of the first EOF mode of SLP anomalies over the southeastern Pacific domain (10° – 45° S, 160° E– 70° W)²⁴. In this study, the signs of both indices are adjusted so that positive (negative) values consistently denote phases conducive to El Niño (La Niña) development, facilitating a unified comparison of their roles in ENSO decay evolution. The monthly SPMM and NPMM indices are defined as the normalized SSTAs averaged over the subtropical southeastern Pacific (25° – 15° S, 90° – 110° W)³⁷ and the subtropical northeastern Pacific (10° – 30° N, 115° – 155° W)³⁸, respectively.

Identified MY and SY ENSO events

In this study, the developing year of an ENSO event is designated as Year (0), the subsequent first ENSO year as Year (1), and the second ENSO year as Year (2). ENSO events in both observations and CESM1 were identified using a consistent criterion based on the Niño 3.4 index. An event was defined when the first-winter Niño 3.4 anomaly [$D(0)JF(1)$] exceeded +0.5 standard deviations (STD) for El Niño or dropped below –0.5 STD for La Niña. Using this definition, we identified 353 El Niño and 384 La Niña events over the 1800-year period in the CESM1 simulation.

The separation of ENSO events into SY and MY types was determined by the persistence of SSTAs into the second winter. An El Niño was classified as SY when its second-winter Niño 3.4 index [$D(1)JF(2)$] was equal to or less than 0.2 STD, and as MY when it remained more than 0.2 STD. Likewise, a La Niña was classified as SY when its second-winter Niño 3.4 index was equal to or larger than –0.2 STD, and as MY when it remained smaller than –0.2 STD. Using this criterion, we identified 161 MY El Niño and 243 MY La Niña events over the 1800-year period in the CESM1 simulation. Previous studies have used thresholds of zero to distinguish MY from SY ENSO events^{21,39}. We tested the criterion and found that the classification differences do not alter the main conclusions of this study. The use of ± 0.2 STD provides a more conservative criterion for defining MY events, ensuring that identified MY events exhibit robust second-year anomalies.

EEOF method

The traditional EOF methods often fail to capture propagating or phase-evolving signals. To overcome this limitation, the extended EOF (EEOF) method incorporates multiple consecutive time slices into the input matrix, enabling the extraction of coupled spatiotemporal evolution patterns^{22,40,41}. In this study, monthly SSTAs for 1940–2024 were divided into 84 overlapping 12-month segments, each spanning from December of Year 0 to November of Year 1 (e.g., Dec 1940–Nov 1941, Dec 1941–Nov 1942, ..., Dec

2023– Nov 2024). These four-dimensional SSTAs ([year] × [month] × [lat] × [lon]) were then reorganized by treating the year dimension as the temporal axis and stacking the anomalies within each 12-month segment along this axis. A conventional EOF analysis was then applied to this reorganized dataset to extract the dominant spatiotemporal modes.

This EEOF approach yields leading modes that depict the evolution of SSTAs from December through November, together with the corresponding 84-year principal component (PC) time series. By construction, each December–November segment captures the evolution of ENSO decaying phases, enabling EEOF to isolate characteristic ENSO evolution pathways that would otherwise be obscured in a traditional EOF analysis.

Declarations

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Data Availability

The ERSST data used in the analysis were downloaded from the National Centers for Environmental Information/National Oceanic and Atmospheric Administration (<https://www.ncei.noaa.gov/products/extended-reconstructed-sst>). The ERA5 monthly reanalysis data is available at <https://cds.climate.copernicus.eu/>. And the CESM1 simulation, which covers a period of 2200 years, was conducted by the CESM project team and is available via the Earth System Grid (<https://www.earthsystemgrid.org/>).

Author Contributions

W.J. and J.Y. designed research; W.J. and Y.J. performed research; W.J. and J.Y. wrote the paper; W.J. analyzed data; X.S., Y.L., G.H., P.H., M.C. and Y.Z. contributed to the interpretation of the results and the improvement of the manuscript. All authors read and approved the final manuscript.

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Figures

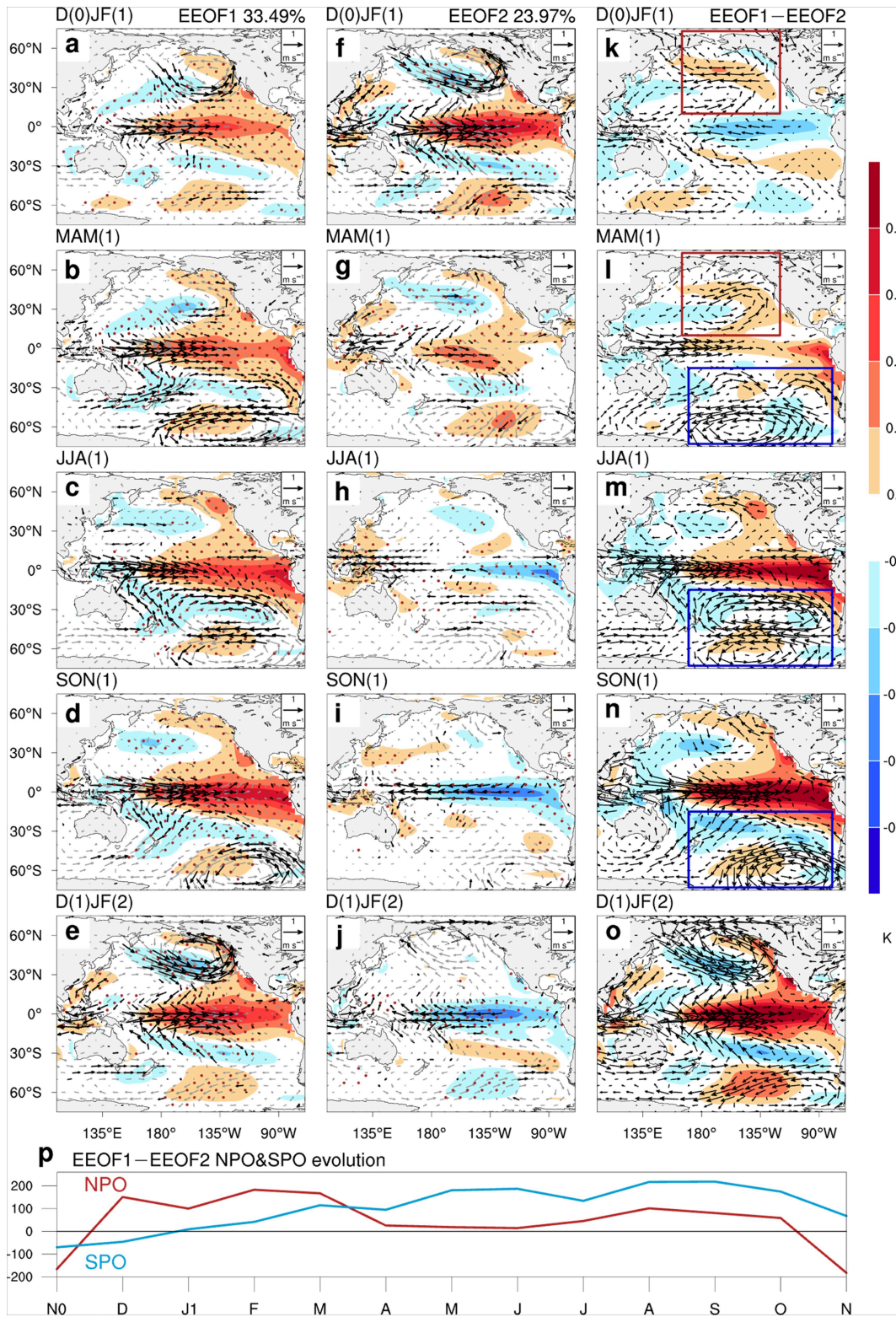


Figure 1

Phase-maintenance and phase-transition ENSO pathways and their associated circulation patterns. Seasonal regressions of SSTAs (shading; K) and 850-hPa wind anomalies (vectors; m s^{-1}) onto **a–e** the EEOF PC1 and **f–j** the EEOF PC2 from the mature winter of developing year [D(0)JF(1)] to the mature winter of the following year [D(1)JF(2)] during 1940–2024. Stippling denotes SSTAs significant at the 95% confidence level, and black vectors denote wind anomalies significant at the 90% confidence level.

k-o Differences between EEOF1 and EEOF2 (EEOF1 – EEOF2) for the corresponding seasons, highlighting their distinct evolutions. **p** Seasonal evolution of the NPO (red line) and SPO (blue line) differences between EEOF1 and EEOF2. Here, the NPO index is defined as the difference in regressed SLP anomalies between a northern box (45°–70°N, 165°E–140°W) and a southern box (10°–35°N, 165°E–140°W). The SPO index is defined as the difference in regressed SLP anomalies between a southern box (45°–70°S, 170°E–80°W) and a northern box (15°–45°S, 170°E–80°W).

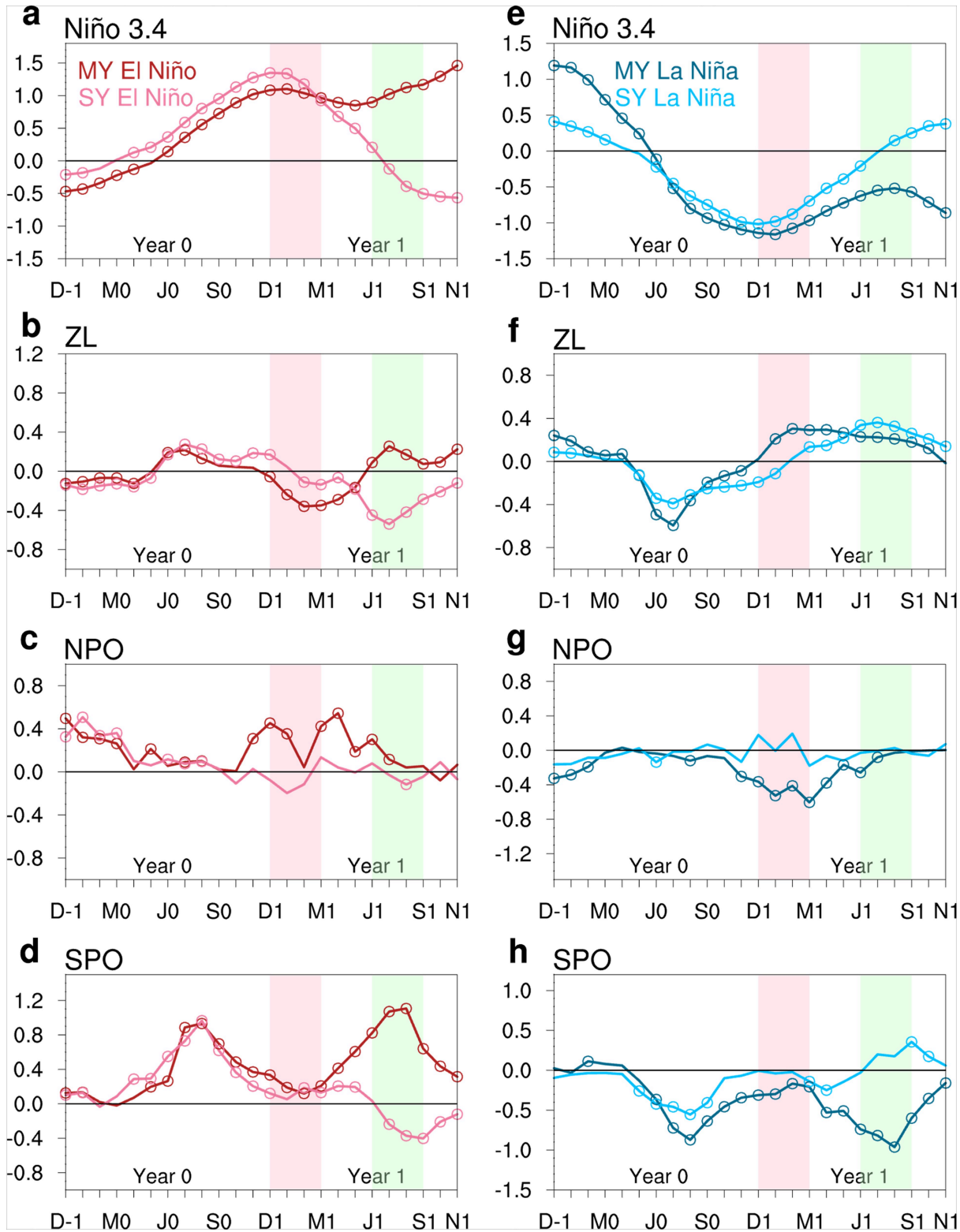


Figure 2

Temporal evolutions of key indices highlighting a hemispheric relay in MY versus SY ENSO events.
Composite evolution of indices for MY and SY ENSO events from the developing year (Year 0) through the subsequent year (Year 1). Niño 3.4 index for **a** El Niño and **e** La Niña. **b, f** Same as **a, e** but for the zonal location index (ZL). NPO index for **c** El Niño and **g** La Niña events. SPO index for **d** El Niño and **h** La Niña events. Circles indicate months in which the MY or SY composite anomaly is significant at the 95% confidence level (two-tailed Student's *t* test). Pink shading denotes the post-peak and early-decay stages of ENSO [D(0)JFM(1)], and the green shading denotes the late-decay stage [JJAS(1)].

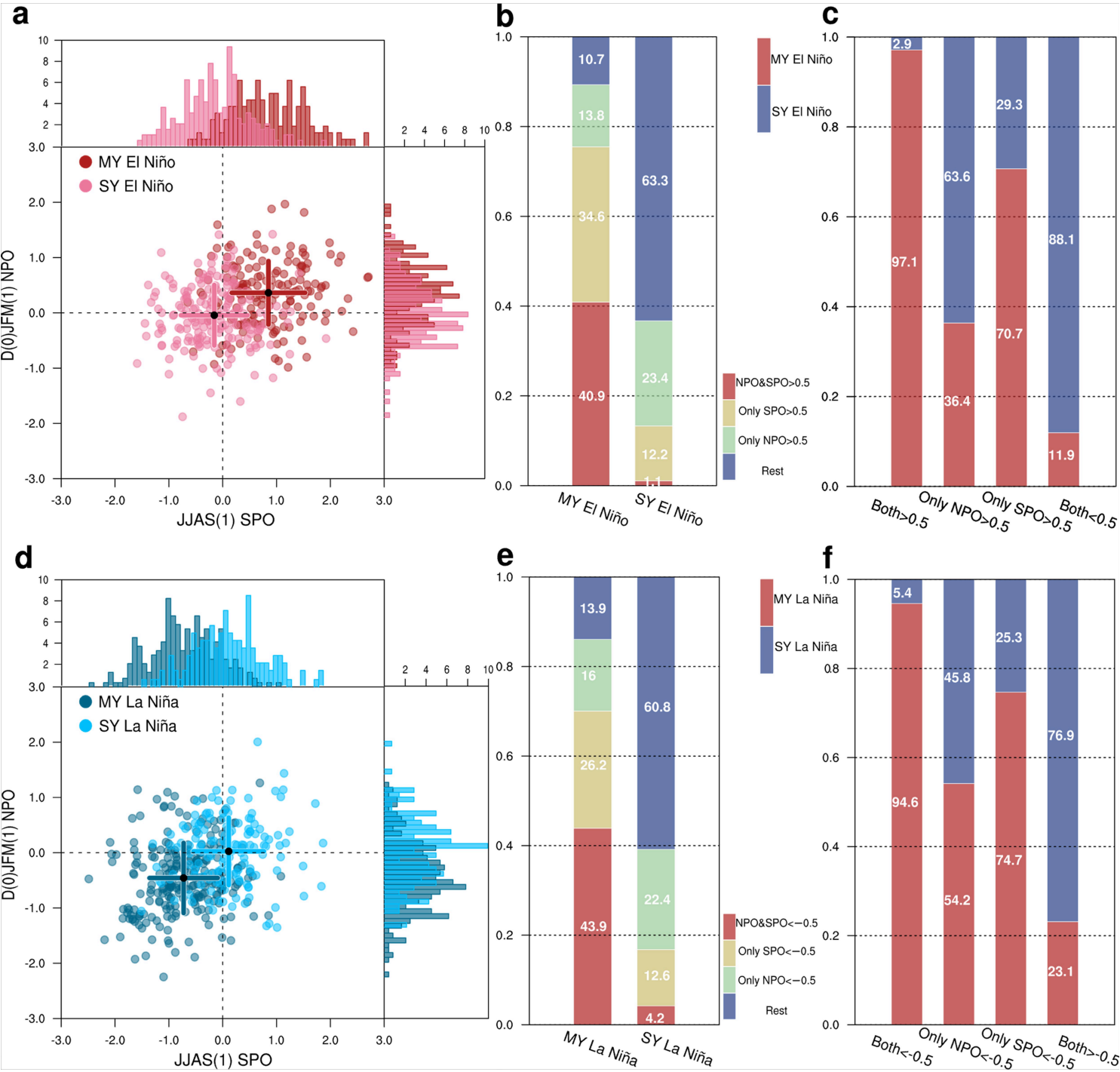


Figure 3

Event-based hemispheric contrasts in extratropical variability for SY versus MY ENSO events.

Scatterplots of the DJFM(1) NPO versus JJAS(1) SPO for **a** El Niño, and **d** La Niña events in the 2,200-year CESM1 preindustrial control simulation. Red and pink dots denote MY and SY El Niño events in **a**, whereas dark and light blue dots represent MY and SY La Niña events in **d**. Histograms along the top and right axes show the marginal distributions of SPO and NPO, respectively. **b, e** Fractions of MY and SY events falling into four NPO–SPO configurations based on ± 0.5 standard deviations threshold: (1) both indices exceed the threshold (red bars), (2) only SPO exceeds the threshold (yellow bars), (3) only NPO exceeds the threshold (green bars), and (4) neither index exceeds the threshold (blue bars). **c, f** Relative percentages (%) of MY (red bars) and SY (blue bars) events within each configuration; numbers on the bars indicate the corresponding percentages.

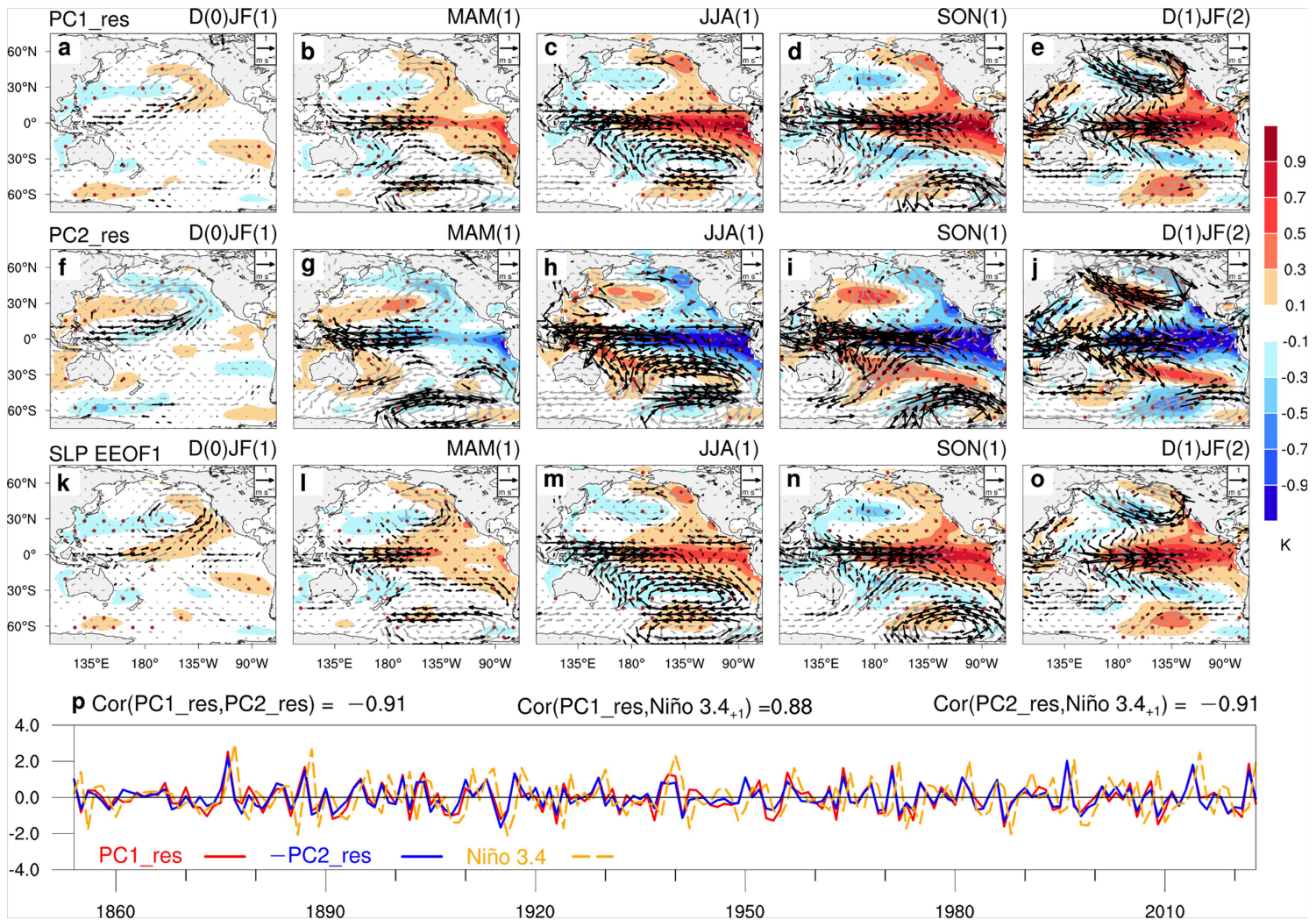


Figure 4

An ENSO-independent hemispheric relay mode underlying ENSO decay diversity. Same as Fig. 1, but for regression patterns obtained after removing the linear influence of mature-phase ENSO signal. Fields are regressed onto **a–e** the residual EEOF PC1 after removing its linear relationship with the D(0)JF(1) CTI

(denoted as PC1_res), and **f–j** the corresponding residual EEOF PC2 (denoted as PC2_res). **k–o** Regression patterns of SSTAs (shading; K) and 850-hPa wind anomalies (vectors; m s^{-1}) onto EEOF1 PC1 from an EEOF analysis of SLP anomalies over 35°S – 35°N , 135°E – 80°W , providing independent support for the relay mode. EEOF1 explains 11.78% of the variance and is well separated by North's test⁴². Stippling denotes SSTAs significant at the 95% confidence level, and black vectors denote wind anomalies significant at the 90% confidence level. **p** Time series of PC1_res (red line), PC2_res multiplied by -1 (blue line) and Niño 3.4 (orange line) over 1854–2024, highlighting the strong antiphase relationship between the two residual PCs and the close linkage to subsequent-year Niño 3.4.

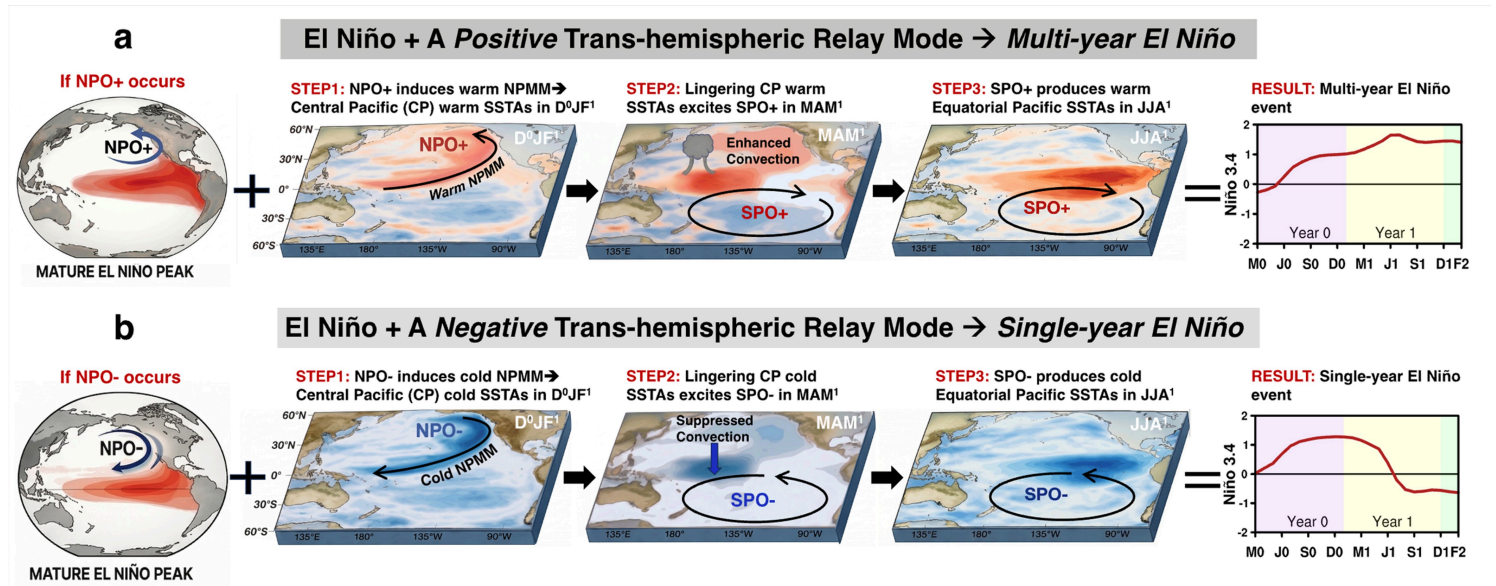


Figure 5

Schematic diagram illustrating the seasonally connected hemispheric relay underlying ENSO decay diversity. **a** Under a positive trans-hemispheric relay mode, a positive NPO during the mature winter of El Niño induces a warm NPMM footprint and warm central-Pacific SSTAs in D(0)JF(1). These lingering warm anomalies persist into MAM(1), favor enhanced convection, and excite a positive SPO. The resulting SPO+ then feeds back onto the equatorial Pacific, generating warm SSTAs in JJA(1) and favoring the persistence of El Niño into a multi-year event. **b** Under a negative trans-hemispheric relay mode, a negative NPO induces a cold NPMM footprint and cold central-Pacific SSTAs in D(0)JF(1). These anomalies persist into MAM(1), suppress convection, and excite a negative SPO. The resulting SPO- then drives cold equatorial Pacific SSTAs in JJA(1), promoting rapid decay and phase reversal of El Niño, and thus leading to a single-year event.

Supplementary Files

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