



Identifying key convection-sensitive oceanic regions to weaken the ENSO spring predictability barrier

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Edited by Carlos Nobre, Universidade de Sao Paulo, Sao Jose dos Campos, Brazil; received May 19, 2025; accepted February 4, 2026

The El Niño–Southern Oscillation (ENSO) exhibits its weakest predictability during boreal spring, a phenomenon known as the Spring Predictability Barrier (SPB). The SPB arises from weak air–sea coupling that limits the growth and persistence of the ENSO signal. Improving springtime prediction therefore requires identifying oceanic regions most relevant for convection variability. Here, we introduce a Sea Surface Temperature Range Index (SRI), which quantifies the spatial extent of Sea surface temperatures favorable for convection. Using SRI, we show that regions exceeding 26 °C in the east-central Pacific and 28.5 °C in the eastern Atlantic during spring are critical for initiating persistent intense convection. The expansion of these convection-sensitive areas strengthens the Bjerknes feedback by modulating the Walker circulation, providing an effective predictor of ENSO evolution. We further develop a Long Short-Term Memory deep learning model incorporating SRI, which achieves higher predictive skill than the average of dynamical and statistical models, especially for multiyear La Niña events. These results underscore the central role of convection-sensitive oceanic regions in alleviating the SPB.

El Niño-southern oscillation | spring predictability barrier | convection | Bjerknes feedback

The El Niño–Southern Oscillation (ENSO) represents the strongest interannual ocean–atmosphere interaction in the tropical Pacific, exerting significant influence on global climate (1–4), ecosystems (5, 6), and human society (7, 8). Accurate ENSO predictions provide policymakers an opportunity to anticipate climatic anomalies, potentially mitigating the adverse socio-economic impacts of this natural phenomenon (9). ENSO predictors of ocean–atmosphere interactions in typical oceanic areas include: the Pacific Niño index (10), Pacific Meridional Mode (PMM) (11), North Tropical Atlantic (NTA) (12), Atlantic Niño (ALT3) index (13). Sea surface temperature (SST) anomalies in these regions modulate local atmospheric convections and promote the development of ENSO events through feedback on the Walker circulation and equatorial zonal wind anomalies (ZWA) (14–17). However, these predictors show the lowest predictive skill during spring, a phenomenon known as the spring predictability barrier (SPB) (18). Several explanations have been proposed. For instance, a reduced zonal SST gradient tends to weaken Pacific air–sea coupling and thereby limits sustained ENSO development (18, 19). Enhanced atmospheric disturbances in both tropical and extratropical regions during spring also amplify stochastic noise, further limiting predictability (20).

The SST variability within tropics is known to significantly influence atmospheric convection changes. Thus, it may be an efficient way to weaken the SPB by identifying the key convection-sensitive oceanic regions in spring (21–24). Previous studies showed that the convections exhibit bell-shaped responses to the rising SST, with their sensitivity rising sharply near a threshold and weakening afterward (21). Specifically, convective activity intensifies sharply when tropical Pacific SST exceeds 27 °C (22, 23), while the sensitivity of convection to SST diminishes once temperature surpasses 29 °C (24). However, current ENSO predictors often focus on monitoring SST changes in fixed oceanic regions, limiting their ability to capture variations in spatial extent (21, 25). This limitation is particularly significant when considering the different persistence barriers in two ENSO types (26), which can influence the predictability barrier.

ENSO indices that account for convective variability have been shown to better represent ENSO's remote climate impacts; one such example is the ENSO Longitude Index, which characterizes the zonal displacement of tropical convection (27). In this study, we propose a SST Range Index (SRI) to quantify variations in SST range and identify key convection-sensitive regions in the tropical Pacific and Atlantic Oceans. The Atlantic Ocean is also considered because Atlantic SST anomalies have been suggested to

Significance

The Spring Predictability Barrier (SPB) remains one of the greatest challenges in forecasting El Niño–Southern Oscillation (ENSO). We introduce a Sea Surface Temperature Range Index (SRI) that measures the spatial extent of Sea surface temperatures conducive to convection in both the Pacific and Atlantic. Thresholds of 26 °C in the east-central Pacific and 28.5 °C in the Atlantic emerge as critical for triggering persistent convection, and the expansion of these regions enhances ocean–atmosphere feedbacks that drive ENSO development. Incorporating SRI into a deep learning model significantly improves ENSO predictions, especially for multiyear La Niña events, offering an approach to overcoming the SPB.

Author contributions: K.F. and D.C. designed research; Z.M., S.L., K.F., W.T., and F.Z. analyzed data; and Z.M., S.L., K.F., W.T., F.L., S.Z., H.W., J.L., Z.Z., T.O., X.X., and D.C. wrote the paper.

The authors declare no competing interest.

This article is a PNAS Direct Submission.

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This article contains supporting information online at <https://www.pnas.org/lookup/suppl/doi:10.1073/pnas.2512725123/-/DCSupplemental>.

Published March 16, 2026.

significantly influence ENSO development (12, 13). By capturing the spatial extent of convection-favorable conditions, the SRI may exert a stronger influence on subsequent ENSO development. Our goal is to investigate how changes in these regions affect ENSO prediction, thereby offering a pathway to weakening the SPB.

Results

Key SST Range of Strong ENSO Predictive Skill. We define the SRI as the normalized index of the cumulative area bounded by each SST isotherm, i.e., areas with SST greater than a given SST isotherm. Areas were calculated using the Cylindrical Equal Area projection method (28). The SRI incorporates dynamic information about SST values and their spatial ranges. We calculated the monthly SRI for isotherms ranging from 25 °C to 30 °C, at 0.5 °C intervals, across the Pacific (120°E to 80°W) and Atlantic (80°W to 20°E) Oceans from 1950 to 2022, spanning

latitude bands of 5°N to 5°S, 10°N to 10°S, 15°N to 15°S, and 20°N to 20°S.

We determine the skillful ENSO predictor as the SRI with strong correlation from spring to its peak phase in winter (SI Appendix, Fig. S1). In the Pacific, the SRI at 26 °C within the 15°N to 15°S range is identified as the key ENSO predictor, showing the highest correlation coefficient of 0.44 ($n = 73$, $P < 0.001$) between spring SRI and winter Niño 3.4 index (Fig. 1A). In the Atlantic, the SRI at 28.5 °C within the 10°N to 10°S range demonstrates the highest predictive ability, with a correlation coefficient of -0.36 ($P < 0.002$) between spring SRI and winter Niño 3.4 index (Fig. 1B). In both ocean basins, the correlation of the SRI surpasses traditional SST-based ENSO predictors, including Niño1 + 2, Niño3, Niño4, Niño3.4, PMM, NTA, and ATL3 (Fig. 1C). Since the SRI is derived from SST fields that may share variability with traditional ENSO indices, it is important to assess whether it contributes independent predictive information. We therefore applied a partial correlation analysis in which the

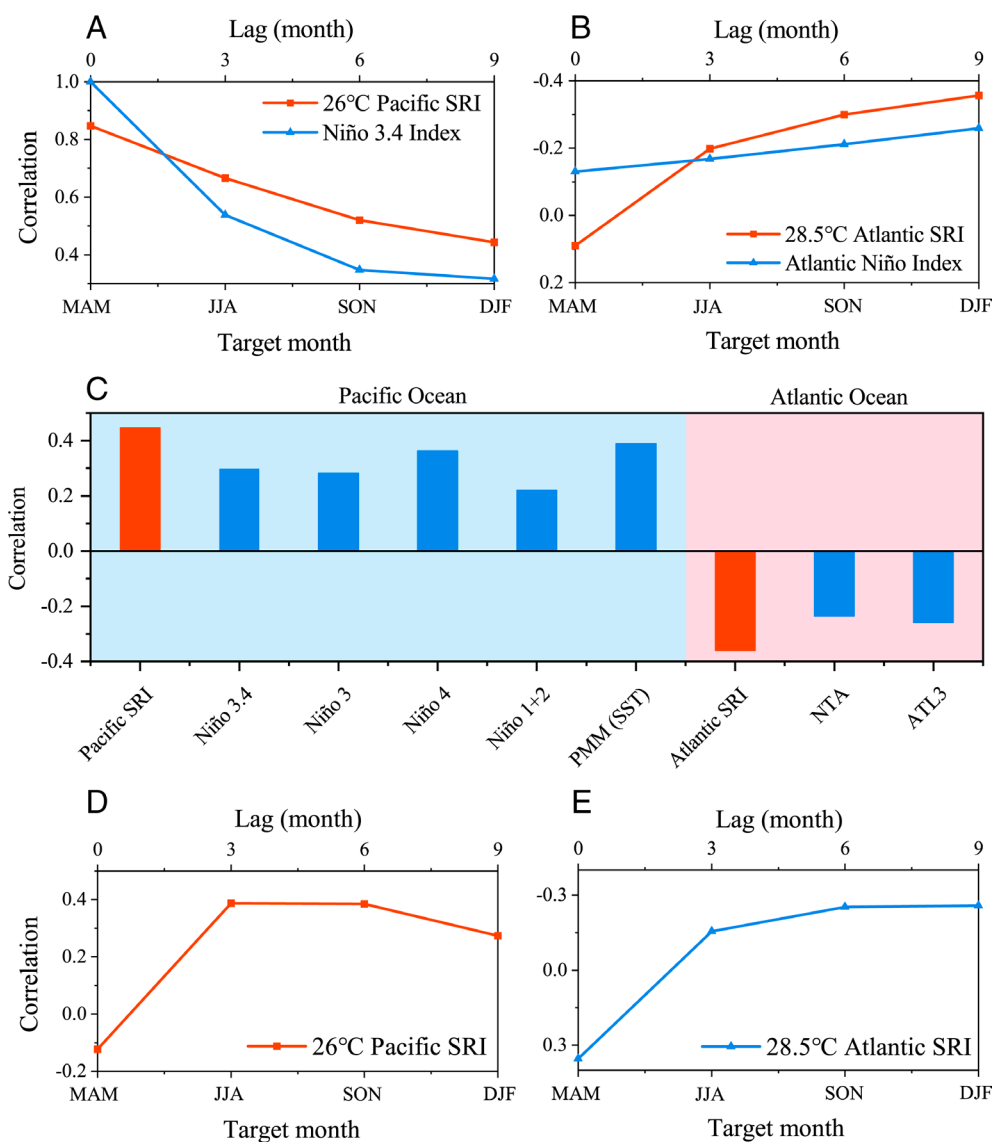


Fig. 1. Comparison of correlations between spring SRI and traditional ENSO indicators with the subsequent seasonal Niño 3.4 index. Spring Pacific 26 °C SRI within the 15°N to 15°S range is correlated with the Niño 3.4 index in subsequent seasons (A). Spring Atlantic 28.5 °C SRI within the 10°N to 10°S range, along with the ALT3 index, is correlated with the Niño 3.4 index in subsequent seasons (B). Comparison of the correlations between the spring SRI in the Pacific and Atlantic and the winter Niño 3.4 index, versus conventional ENSO indicators based on SST anomalies (C). Partial correlations between the spring Pacific SRI and the Niño 3.4 index in subsequent seasons, after regressing out spring SST anomalies across all Pacific Niño regions (5°N to 5°S, 160°E to 80°W) and PMM (D). Partial correlations between the spring Atlantic SRI and the Niño 3.4 index in subsequent seasons, after regressing out the influence of the spring ALT3 index (E).

influences of SST anomalies from the traditional predictor regions (i.e., the Pacific and ALT3 regions and PMM) were removed. After removing these effects, the Pacific SRI maintains a significant partial correlation of 0.27 ($P < 0.02$), and the Atlantic SRI remains significantly correlated at -0.26 ($P < 0.05$) with the winter Niño 3.4 index (Fig. 1 D and E). These results demonstrate that the spring SRI captures independent and physically meaningful information, serving as a robust standalone predictor of ENSO evolution.

The SRI also demonstrates stronger predictive ability by capturing the spatial evolution of the SST patterns associated with different ENSO types. For example, during the spring of Eastern Pacific (EP) El Niño (single-year La Niña) events, the 26 °C isotherm primarily expands (contracts) in the equatorial EP (SI Appendix, Fig. S2 A and C), a pattern observed in 13 of 15 El Niño events and 7 of 9 La Niña events (SI Appendix, Fig. S3 A). In contrast, during Central Pacific (CP) El Niño (multiyear La Niña) events, the 26 °C isotherm expansion (contraction) occurs further from the equator, primarily near 15°N to 15°S in the east-CP (SI Appendix, Fig. S2 B and D), observed in 7 of 9 El Niño events and 9 of 12 La Niña events (SI Appendix, Fig. S3 B).

In the Atlantic, during the spring of EP El Niño events, the 28.5 °C isotherm in the equatorial eastern Atlantic undergoes significant contraction (SI Appendix, Fig. S4 A), observed in 9 out of 15 events (SI Appendix, Fig. S5 A). In contrast, during CP El Niño events, the isotherm in the eastern Atlantic slightly expands, while warming in the western Atlantic causes localized SST to exceed 28.5 °C (SI Appendix, Fig. S4 B). Together, these regions contribute to the expansion of the Atlantic 28.5 °C SST range, occurring in 5 out of 9 events (SI Appendix, Fig. S5 B). Single-year and multiyear La Niña events exhibit a 28.5 °C isotherm expansion pattern similar to that of CP El Niño, but with a larger extent (SI Appendix, Fig. S4 C and D), observed in 14 out of 21 events (SI Appendix, Fig. S5 A and B). Notably, the additional analysis confirms that springtime SRI changes are more evident in super El Niño years, with clearer expansion in the Pacific and contraction in the equatorial Atlantic (SI Appendix, Figs. S6–S8).

Thresholds Toward Strong SST-Convection Relationship. The variability of SST ranges tends to trigger ENSO events via modulating convection activity (21). We thus calculated convection intensity within different SST ranges in the EP and the Atlantic using the Outgoing Longwave Radiation (OLR), a widely used proxy for convection strength (29), focusing on regions where the 26 °C and 28.5 °C isotherms exhibit significant variability (Fig. 2 A and B). In the EP, convective activity stays at a low level below 26 °C and steadily intensifies between 26 °C and 28 °C (Fig. 2 C). The sensitivity of SST to convection begins to rise slowly at 26 °C (Fig. 2 E), showing a clear threshold effect. Rising convections beyond a threshold of 26 °C agrees with the strongest ENSO predictability of SRI above 26 °C revealed above, supporting the SRI triggering ENSO via modulating convection in the Pacific.

In the Atlantic, convection intensifies rapidly with increasing SST, particularly above 27 °C (Fig. 2 D). Unlike the EP, convection sensitivity increases sharply beyond 28 °C, peaking at 28.5 °C (Fig. 2 F). Strongest convection with the 28.5 °C SST range agrees with the SRI of strongest ENSO prediction skill in the Atlantic, further supporting SRI-induced convection is a key for ENSO prediction during spring.

Atmospheric Circulations Linking SRI to ENSO Development. A larger Pacific SRI is associated with an expansion of SSTs exceeding the 26 °C convection threshold, promoting more extensive and persistent atmospheric convection (SI Appendix, Fig. S9).

The enhanced convection, in turn, modulates both the surface wind field and geopotential height (GPH), producing equatorially symmetric westerly anomalies across the tropical Pacific (SI Appendix, Fig. S10).

These results reflect the SRI's role in suppressing the Walker circulation and promoting low-level westerly anomalies that favor the onset and development of El Niño events (30). In contrast, the Atlantic 28.5 °C SRI enhances local deep convection over the tropical Atlantic (SI Appendix, Fig. S11) and induces subsidence over the CP, strengthening easterly anomalies that drive warm water westward and cool the EP, thereby favoring La Niña development (31–33) (SI Appendix, Fig. S12). Although the spatial patterns associated with both SRIs resemble those linked to the Niño 3.4 and ALT3, respectively, the SRI exhibits stronger and more persistent impacts on wind and pressure fields in the following seasons, highlighting its advantage in exciting large-scale ocean–atmosphere feedbacks.

Furthermore, after removing the effects of spring SST anomalies across the Pacific Niño regions and PMM, the Pacific SRI remains significantly positively correlated with SST on both sides of the equator in the central and EP (Fig. 3 A), indicating that a larger SRI corresponds to a broader meridional extent of warm SSTs in spring. This SST pattern induces two anticyclonic circulation anomalies: One over the off-equatorial north-CP and the other over the off-equatorial southeast Pacific (Fig. 3 A). The circulation anomalies generate negative wind-stress curl on both flanks of the equator, which drives equatorward Sverdrup transport and thereby promotes warm-water recharge along the equator in the following summer (34) (Fig. 3 B).

The Pacific SRI-associated expansion of warm SSTs persists into the following summer and autumn, with warm SSTs and accompanying westerly winds emerging along the equator. These westerly winds can induce eastward transport of warm water and generate downwelling Kelvin waves that propagate into the eastern equatorial Pacific, contributing to a deepening of the thermocline. The positive spatial correlation between the Pacific SRI and SSH anomalies along the equator supports this mechanism (Fig. 3 B). Meanwhile, the associated equatorial Ekman convergence counteracts the geostrophic discharge that typically facilitates ENSO phase transitions (35). As a result, upper-ocean heat content anomalies are maintained through boreal summer and autumn, which create favorable conditions for the development and persistence of El Niño events in the following winter.

A similar meridionally broad SST structure is also associated with the Atlantic 28.5 °C SRI, which shows strong correlations with SST anomalies on both sides of the equator over the tropical Atlantic (SI Appendix, Fig. S13). This structure enhances local convection, which induces easterly wind anomalies over the EP that contribute to surface cooling and support La Niña development (SI Appendix, Fig. S13).

Given the opposing roles of the Pacific and Atlantic SRIs in modulating ENSO evolution, we constructed a spring SRI difference index (Pacific minus Atlantic) to quantify their combined effect on equatorial convection. Indeed, the spring SRI difference exerts a stronger influence on winter pressure and wind fields, as indicated by their spatial correlation patterns (SI Appendix, Fig. S14), compared to using the Pacific or Atlantic SRI alone. As a result, the spring Pacific-Atlantic SRI difference shows a higher correlation with the winter Niño 3.4 index ($r = 0.64$, $P < 0.001$) (SI Appendix, Fig. S15 A).

Low SRI differences are associated with the contraction of convection-sensitive SST in the EP during spring, leading to weakened convection and an intensified descending branch of the Walker circulation. Meanwhile, the expansion of convection-sensitive SST

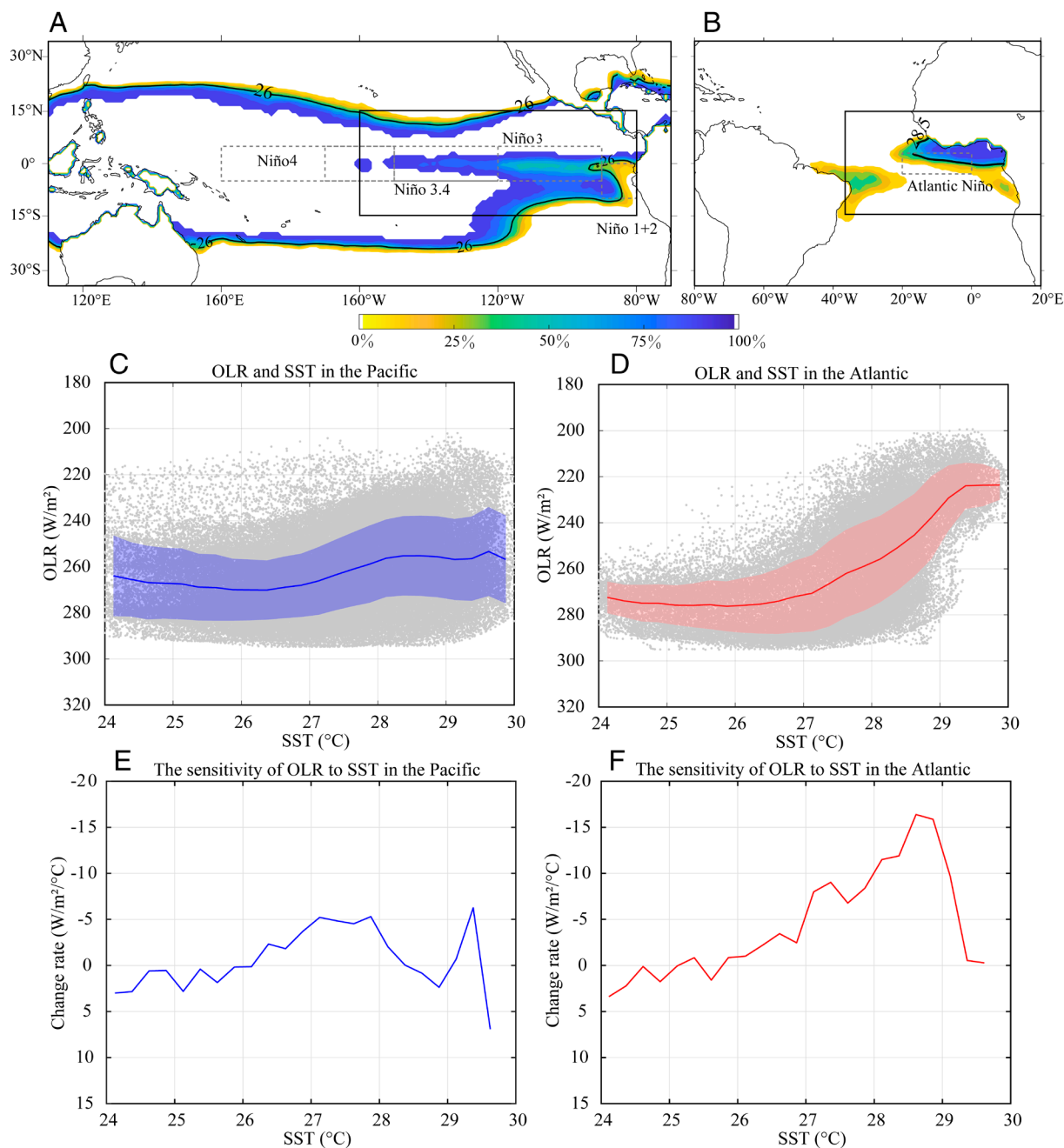


Fig. 2. Spring SST range changes in the Pacific and Atlantic and their relationship with convection. Percentages of spring SST grid points exceeding 26 °C in the Pacific and 28.5 °C in the Atlantic during 1950 to 2022, respectively; the 0% and 100% values are filled with white (A and B). Scatterplots of OLR in each 0.25 °C SST bin for Pacific and Atlantic (C and D). Colored line segments represent the average OLR within each 0.25 °C SST bin, with shading indicating ± 1 SD from the bin mean. The scatter plots correspond to the boxed regions in panels A and B. Sensitivity of Pacific 26 °C SST and Atlantic 28.5 °C SST to OLR, highlighting the relationship between SST and convection (E and F).

in the western Pacific and Atlantic strengthens convection there, enhancing the ascending branch of the Walker circulation. This combined Walker circulation reinforces subsidence over the EP, driving strong equatorial easterly winds that push warm water westward (36, 37) (Fig. 4). The wind forcing also generates westward-propagating oceanic Rossby waves along the off-equatorial Pacific, which intensify warming in the western Pacific (38), while the associated eastward-propagating upwelling Kelvin waves steepen the thermocline slope along the equatorial Pacific (39). Additionally, atmospheric Kelvin waves originating from the warmer Atlantic propagate eastward, interact with the Maritime Continent, and induce localized Walker circulation over the western Pacific, thereby enhancing the strength of the Bjerknes feedback (30, 40).

The combined effects of the above processes accelerate the development of La Niña events (Fig. 4).

SRI-Based ENSO Prediction Model. As the spring Pacific–Atlantic SRI difference exhibits the highest prediction skill, we developed a prediction model that incorporates this metric alongside traditional ENSO predictors. The predictors include ZWA (41), PMM (wind) (11), and warm water volume (WWV) (42), with spring-to-winter Niño 3.4 correlations of 0.69, 0.52, and 0.59, respectively (SI Appendix, Fig. S15 B–D). ENSO prediction initiated from spring was performed using an advanced deep learning-based time series predicting approach, the Long Short-Term Memory (LSTM) method (43, 44).

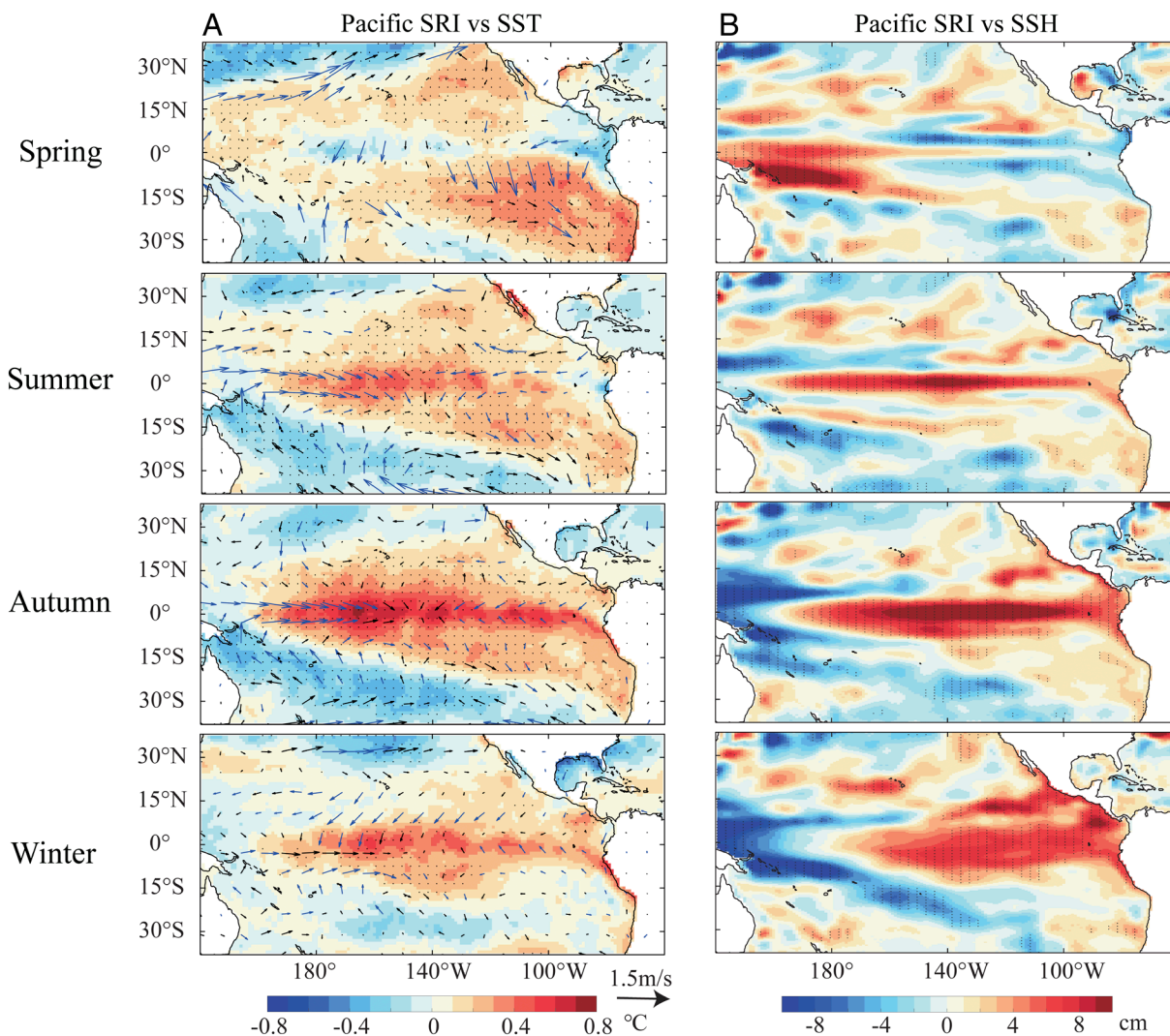


Fig. 3. Influence of the Pacific SRI on SST, wind fields, and sea surface height (SSH). Partial regression of the spring Pacific SRI with SST anomalies and surface wind fields in spring, summer, autumn, and winter, after regressing out spring SST anomalies across all Pacific Niño regions and PMM (A). Partial regression of the spring Pacific SRI with SSH anomalies in spring, summer, autumn, and winter, after regressing out spring SST anomalies across all Pacific Niño regions and PMM (B). Black dots and blue vectors indicate the regression coefficients significantly above the 95% confidence level.

When using only traditional predictors (ZWA, PMM, and WWV), the LSTM model achieved correlations of 0.75 ($P < 0.001$) and 0.72 ($P < 0.001$) during the training (1950 to 2000) and testing periods (2001 to 2022), respectively (*SI Appendix, Fig. S16A*). With the inclusion of the spring Pacific–Atlantic SRI difference proposed in this study, the predictive skill improved to 0.81 ($P < 0.001$) and 0.78 ($P < 0.001$), respectively, for the winter Niño 3.4 index (*Fig. 5A*). Adding the Pacific–Atlantic SRI difference to the LSTM model reduces year-wise absolute prediction error and yields the largest improvement in correlation relative to adding individual traditional indices (Niño-1 +2/3/4/3.4 or ATL3) (*SI Appendix, Table S1*), with the correlation improvement significant at the 5% level (left-tailed paired t test, $P = 0.048$, *SI Appendix, Fig. S17*). Besides, retraining the SRI model on alternative periods (1960 to 2000, 1970 to 2000, 1980 to 2000) and testing on 2001 to 2022 yields similar skill, indicating robustness across distinct climatic backgrounds (*SI Appendix, Fig. S18*), including the late-1970 s Pacific decadal oscillation phase shift (45).

To further quantify the role of each predictor in the LSTM model, we applied the Shapley Additive Explanations framework (46) to compute mean absolute Shapley values, which measure the marginal contribution of each predictor. The results confirm

that SRI is the dominant contributor (*SI Appendix, Fig. S19*). Partial regressions that additionally remove the influence of PMM, ZWA, and WWV still show that the spring Pacific SRI is associated with equatorial SST anomalies in subsequent seasons (*SI Appendix, Fig. S20*), confirming that SRI provides independent predictor information. To assess the robustness of the model and rule out overfitting, we reversed the training (2001 to 2022) and testing (1950 to 2000) periods. The model still achieved high correlations of 0.78 ($P < 0.001$) and 0.80 ($P < 0.001$), respectively (*SI Appendix, Fig. S16B*). Additionally, we used early stopping with a temporal validation split and stopped at the validation-loss minimum (47); the model showed no train–validation divergence and generalized well to 2001 to 2022 (*SI Appendix, Fig. S21*), indicating no overfitting.

Between 1950 and 2022, it successfully predicted 21 of 24 El Niño events and 20 of 21 La Niña events (*Fig. 5B and C*). Prediction errors varied across ENSO types, with the highest MAE (48) of 0.62 for CP El Niño, followed by 0.61 for EP El Niño. The model showed greater accuracy for La Niña events, particularly multiyear La Niña, with MAE values of 0.45 and 0.37 for single-year and multiyear La Niña events, respectively (*Fig. 5B and C*). While the model exhibited modest performance in

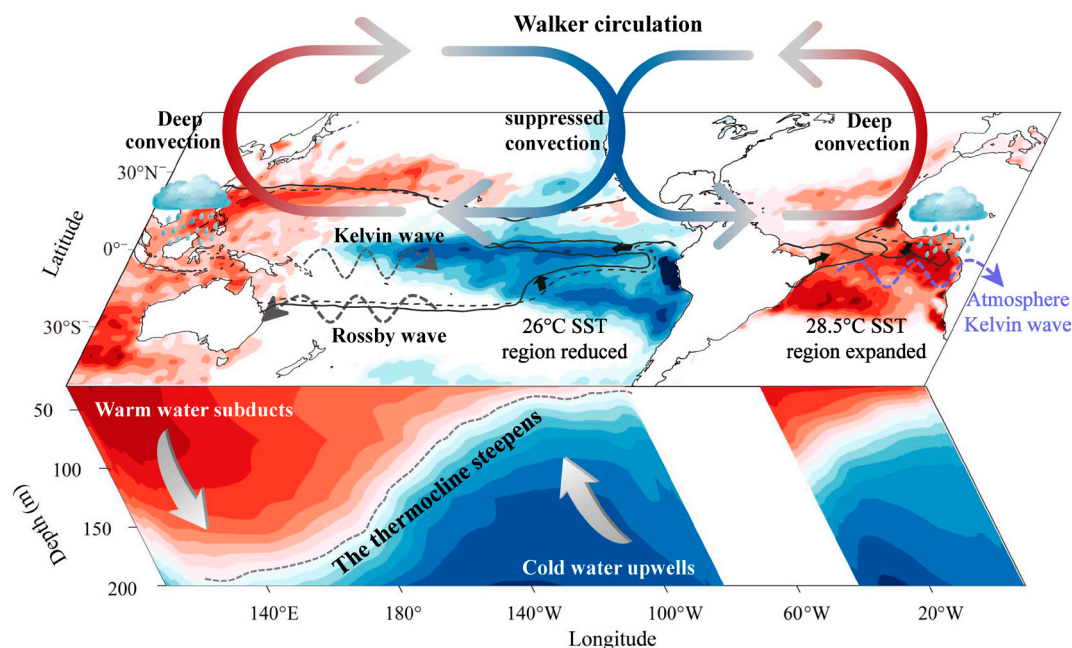


Fig. 4. Schematic of springtime Pacific and Atlantic SST variations driving convection and facilitating La Niña events. The ascending convection in the western Pacific and Atlantic, combined with the descending convection in the EP, forms a Walker circulation spanning both oceans. This process significantly strengthens the equatorial easterlies, pushing warm water westward and steepening the equatorial thermocline. The combined influence of the Pacific and Atlantic drives the development of La Niña.

predicting the winter Niño 3.4 index in the early 21st century, with correlations near 0.6, its accuracy improved markedly from 2013 onward, reaching correlations of approximately 0.9, substantially surpassing the average predictive skill of existing dynamical and statistical models (Fig. 5 D and E).

Discussion

Previous studies suggested that El Niño is more predictable than La Niña because its development is accompanied by a stronger zonal wind stress response and enhanced zonal advection/thermocline feedback, thereby weakening the SPB and improving El Niño predictability (49, 50). In this study, we find that the LSTM model significantly outperforms in predicting multiyear La Niña events compared to El Niño events. We suggest that this discrepancy is not due to the superior predictive power of any particular factor in the model for multiyear La Niña (SI Appendix, Fig. S22), but rather stems from the LSTM model that effectively captures the long-term dependencies among system variables, particularly in identifying the accumulation and changes of precursor signals associated with ENSO evolution (43). Unlike El Niño events that typically exhibit strong positive feedback and relatively rapid changes (51, 52), multiyear La Niña events are characterized by the sustained expansion of cold water regions and the long-term strengthening of easterly winds. These changes are more stable and accumulate gradually, revealing distinct long-term evolutionary characteristics (51, 52). The LSTM model, through its memory units, effectively captures these long-term nonlinear dependencies and identifies the progressive patterns associated with La Niña events within the time series (53), thereby significantly enhancing the prediction accuracy for multiyear La Niña.

This study introduces the SRI to quantify changes in SST ranges and reveals that regions with SST above 26 °C in the east-CP and 28.5 °C in the Atlantic are key for ENSO prediction. The expansion of the convection-sensitive SST area enhances convection-driven ocean–atmosphere coupling, including the Bjerknes feedback, facilitating the onset and development of ENSO events and

outperforming traditional SST-based ENSO predictors. Building on the SRI, our LSTM prediction model effectively captures critical SST anomalies and feedback mechanisms, significantly improving the prediction of ENSO events, particularly multiyear La Niña events. The ongoing refinement of the LSTM model holds great potential for advancing ENSO predictions, particularly in addressing the challenges posed by the increasing frequency of multiyear La Niña events (54–56). Previous studies argued that the SST threshold for convection may increase under global warming (57), implying that the SRI thresholds may also vary over time. Nevertheless, to ensure sufficient sample size for statistical analyses and for training the LSTM model, we adopted fixed thresholds (i.e., 26 °C and 28.5 °C) based on the overall SST–convection relationship during 1950 to 2022. Future work should investigate the potential impacts of time-varying SRI thresholds on ENSO predictability.

Materials and Methods

Climate Data. This study used monthly SST data from the Hadley Centre Sea Ice and Sea Surface Temperature dataset (HadISST), which has a $1^\circ \times 1^\circ$ grid and spans from 1870 onward (58). We restrict to 1950 onward to reduce measurement biases and improve reliability (59). GPH and wind data were obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis version 5 (ERA5), offering a spatial resolution of $0.25^\circ \times 0.25^\circ$ and covering the period from 1950 to the present (60). The monthly OLR Climate Data Record, spanning 1979 to present, provides $2.5^\circ \times 2.5^\circ$ resolution data (61). The precipitation data used in this study are from the Global Precipitation Climatology Project (GPCP) monthly dataset (version 2.3), available since 1979 with a spatial resolution of $2.5^\circ \times 2.5^\circ$ (62). The SSH data were obtained from the National Centers for Environmental Prediction Global Ocean Data Assimilation System (GODAS), covering the period from 1980 to 2022 (63). ENSO forecasts data initiated from spring were derived from the International Research Institute for Climate and Society (IRI) since 2002 based on dynamical and statistical models (64). Considering that ENSO-related ocean–atmosphere interactions may exhibit submonthly variability, especially during strong ENSO events (65), we also calculated the SRI using daily SST

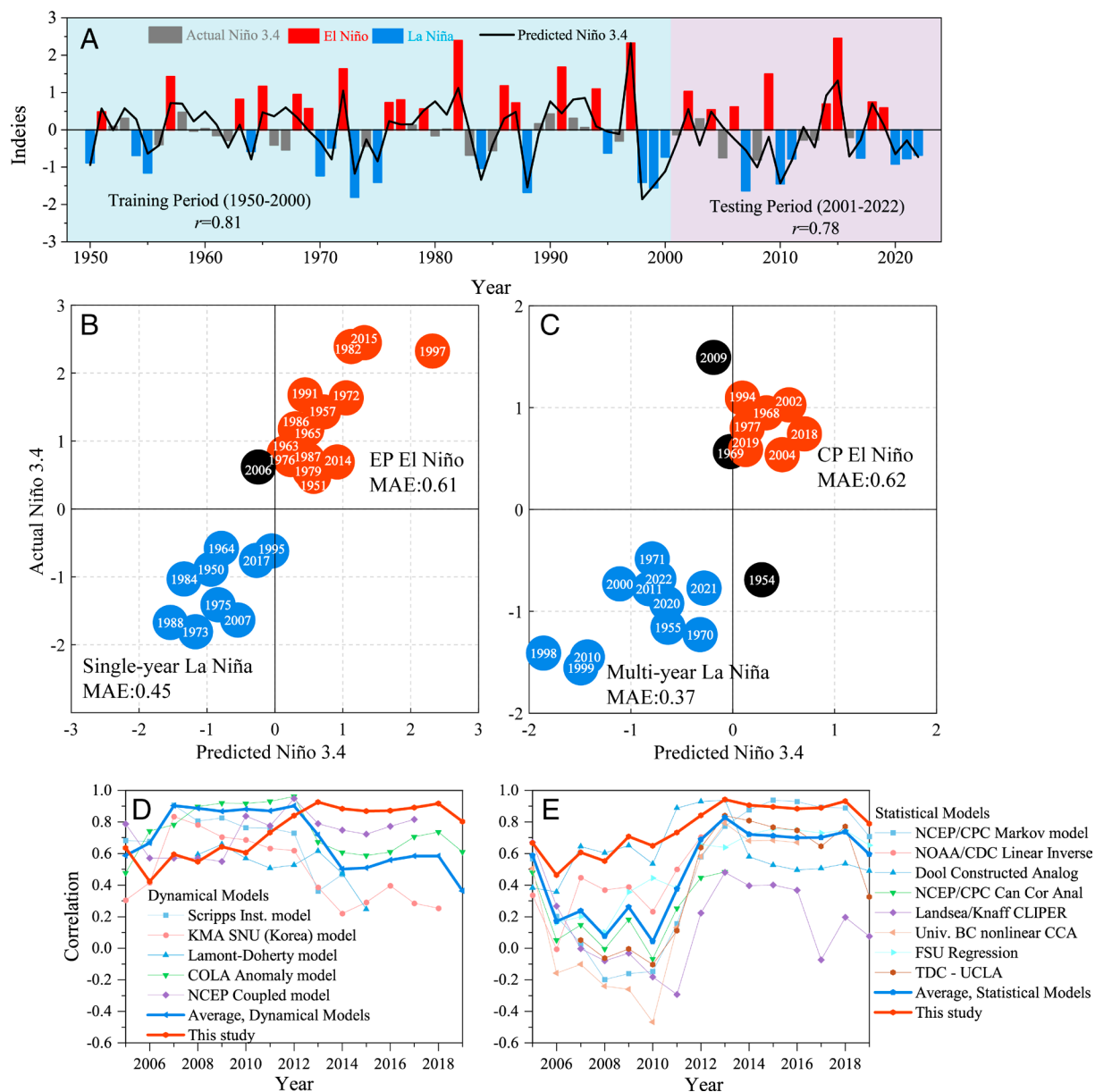


Fig. 5. Predictive skill of the LSTM model for the Niño 3.4 index. Comparison between the Niño 3.4 index predicted by the LSTM model and the observed Niño 3.4 index (A). Scatter plot of LSTM learning model predictions of the Niño 3.4 index in spring for EP El Niño and single-year La Niña events, compared to observed winter Niño 3.4 values (B). Similar scatter plot for CP El Niño and multiyear La Niña events. Red and blue circles indicate correctly predicted El Niño and La Niña events, respectively, while black circles represent incorrect predictions. The numbers within the circles denote the years when the warning signals were issued. The Mean Absolute Error (MAE) is the mean of the absolute differences between the predicted values and the actual values (C). Predictive skill comparison of the LSTM model with dynamic models and statistical models, based on the 7-y running correlation between model predictions and observed Niño 3.4 index values from 2002 to 2022 (D and E).

data from the NOAA High-resolution Blended Analysis of Daily SST and Ice ($0.25^\circ \times 0.25^\circ$ global grid, available from September 1981 onward) (66). The springtime variations of the SRI based on daily data are nearly identical to those derived from monthly data (SI Appendix, Figs. S6–S8), confirming the robustness of using monthly SSTs in our analyses.

Definition of Traditional ENSO Predictors. ENSO indices are based on SST anomalies in different Pacific regions. Niño 1 + 2 corresponds to 0 to 10°S , 90°W to 80°W ; Niño 3 to 5°N to 5°S , 150°W to 90°W ; Niño 4 to 5°N to 5°S , 160°E to 150°W ; and Niño 3.4 to 5°N to 5°S , 170°W to 120°W . An El Niño (La Niña) event occurs when the Niño 3.4 anomalies exceed $+0.5^\circ\text{C}$ (below -0.5°C) for five consecutive months (67). Using this criterion, 24 El Niño events and 21 La Niña events were identified between 1950 and 2022 (SI Appendix, Table S2). El Niño events were classified as Eastern or CP types based on whether the East Pacific

type of El Niño/La Niña index or the CP type of El Niño/La Niña index exceeded $\pm 0.5^\circ\text{C}$ for at least three consecutive months during the event, following widely used operational definitions (68). La Niña events were further categorized as single-year or multiyear types depending on whether the identified La Niña years occurred consecutively (SI Appendix, Table S2).

The WWV is defined as the volume of warm water above the 20°C isotherm in the equatorial Pacific region (5°N to 5°S , 120°E to 80°W) (42). The PMM index is derived using Maximum Covariance Analysis between SST and 10 m wind fields over the region 21°S to 32°N , 74°W to 15°E (11). ZWA refers to deviations from the equatorial surface zonal wind anomaly averaged over the region 5°S to 5°N , 137°E to 167°E during spring (41). The ALT3/Niña is quantified by SST anomalies averaged over the cold-tongue region (3°S to 3°N , 20°W to 0°) (13). The NTA reflects SST anomalies in the northern tropical Atlantic (5°N to 25°N , 15°W to 60°W) (12).

ENSO Prediction Model. We used the widely adopted LSTM model to predict winter ENSO events starting from spring (43, 44). LSTM, with its memory cells and gating mechanisms, is well suited for capturing long-term dependencies in sequential data (69). This makes it particularly effective for ENSO prediction by retaining relevant patterns in historical SST anomalies while filtering out noise (59). The LSTM model was trained using data from 1950–2000 to capture the complex seasonal dynamics associated with ENSO events. Its performance was then tested by predicting the winter Niño 3.4 index during the independent period of 2001 to 2022.

Data, Materials, and Software Availability. The HadISST dataset is available at (<https://hadleyserver.metoffice.gov.uk/hadisst/>) (58). NOAA High-resolution Blended Analysis of Daily SST and Ice data is available at (<https://www.psl.noaa.gov/data/gridded/data.noaa.oisst.v2.highres.html>) (66). ECMWF Reanalysis version 5 dataset is available at (<https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-interim>) (60). The OLR data are available at (<https://www.ncei.noaa.gov/products/climate-data-records/outgoing-longwave-radiation-monthly>) (61). The SSH dataset is available at (<https://www.psl.noaa.gov/data/gridded/data.godas.html>) (63). The GPCP dataset is available at (<https://psl.noaa.gov/data/gridded/data.gpcp.html>) (62). The ENSO forecast data from IRI are available at (<https://iri.columbia.edu/our-expertise/climate/ensoi/>) (64).

- W. Cai *et al.*, Changing el niño-southern oscillation in a warming climate. *Nat. Rev. Earth Environ.* **2**, 628–644 (2021).
- A. Timmermann *et al.*, El Niño-southern oscillation complexity. *Nature* **559**, 535–545 (2018).
- J. M. Arblaster, L. V. Alexander, The impact of the El Niño-Southern oscillation on maximum temperature extremes. *Geophys. Res. Lett.* **39**, 2012GL053409 (2012).
- M. J. McPhaden, S. E. Zebiak, M. H. Glantz, ENSO as an integrating concept in earth science. *Science* **314**, 1740–1745 (2006).
- S. M. Hsiang, K. C. Meng, M. A. Cane, Civil conflicts are associated with the global climate. *Nature* **476**, 438–441 (2011).
- K. Fang *et al.*, ENSO modulates wildfire activity in China. *Nat. Commun.* **12**, 1764 (2021).
- A. K. Heaney, J. Shaman, K. A. Alexander, El Niño-Southern oscillation and under-5 diarrhea in Botswana. *Nat. Commun.* **10**, 5798 (2019).
- A. Haines, H. C. Y. Lam, El niño and health in an era of unprecedented climate change. *Lancet* **402**, 1811–1813 (2023).
- Y. Tang *et al.*, Progress in ENSO prediction and predictability study. *Natl. Sci. Rev.* **5**, 826–839 (2018).
- S. Zhao *et al.*, Explainable El Niño predictability from climate mode interactions. *Nature* **630**, 891–898 (2024).
- J. C. H. Chiang, D. J. Vimont, Analogous meridional modes of atmosphere-ocean variability in the tropical Pacific and tropical Atlantic. *J. Clim.* **17**, 4143–4158 (2004).
- Y.-G. Ham, J.-S. Kug, J.-Y. Park, F.-F. Jin, Sea surface temperature in the north tropical Atlantic as a trigger for El Niño/Southern oscillation events. *Nat. Geosci.* **6**, 112–116 (2013).
- Y. Yang *et al.*, Suppressed Atlantic Niño/Niña variability under greenhouse warming. *Nat. Clim. Chang.* **12**, 814–821 (2022).
- R. Ding *et al.*, Multi-year El niño events tied to the North Pacific oscillation. *Nat. Commun.* **13**, 3871 (2022).
- F. Jia, W. Cai, B. Gan, L. Wu, E. Di Lorenzo, Enhanced north Pacific impact on El Niño/southern oscillation under greenhouse warming. *Nat. Clim. Change* **11**, 840–847 (2021).
- J.-W. Kim, J.-Y. Yu, B. Tian, Overemphasized role of preceding strong El Niño in generating multi-year La Niña events. *Nat. Commun.* **14**, 6790 (2023).
- M. Martín-Rey, B. Rodríguez-Fonseca, I. Polo, Atlantic opportunities for ENSO prediction. *Geophys. Res. Lett.* **42**, 6802–6810 (2015).
- P. J. Webster, S. Yang, Monsoon and ENSO: Selectively interactive systems. *Q. J. R. Meteorol. Soc.* **118**, 877–926 (1992).
- E. K. Jin *et al.*, Current status of ENSO prediction skill in coupled ocean-atmosphere models. *Clim. Dyn.* **31**, 647–664 (2008).
- Y. Jin, Z. Liu, W. Duan, The different relationships between the ENSO spring persistence barrier and predictability barrier. *J. Climate* **35**, 6207–6218 (2022).
- R. Xie, M. Mu, X. Fang, New indices for better understanding ENSO by incorporating convection sensitivity to sea surface temperature. *J. Climate* **33**, 7045–7061 (2020).
- S. Gadgil, P. V. Joseph, N. Joshi, Ocean-atmosphere coupling over monsoon regions. *Nature* **312**, 141–143 (1984).
- N. E. Graham, T. P. Barnett, Sea surface temperature, surface wind divergence, and convection over tropical oceans. *Science* **238**, 657–659 (1987).
- S. Lin *et al.*, Attribution of the seasonality of atmospheric heating changes over the western tropical Pacific with a focus on the spring season. *Clim. Dyn.* **58**, 2575–2592 (2022).
- K. M. Lau, H. T. Wu, S. Bony, The role of large-scale atmospheric circulation in the relationship between tropical convection and sea surface temperature. *J. Climate* **10**, 381–392 (1997).
- H. L. Ren, F. F. Jin, B. Tian, A. A. Scaife, Distinct persistence barriers in two types of ENSO. *Geophys. Res. Lett.* **43**, 10–973 (2016).
- I. N. Williams, C. M. Patricola, Diversity of ENSO events unified by convective threshold sea surface temperature: A nonlinear ENSO index. *Geophys. Res. Lett.* **45**, 9236–9244 (2018).
- J. P. Snyder, “Map projections—A working manual” (U.S. Geological Survey Professional Paper 1395, US Government Printing Office, Washington, DC, USA, 1987).
- B. Liebmann, C. A. Smith, Description of a complete (interpolated) outgoing longwave radiation dataset. *Bull. Am. Meteorol. Soc.* **77**, 1275–1277 (1996).
- J. Bjerknes, Atmospheric teleconnections from the equatorial Pacific. *Mon. Weather Rev.* **97**, 163–172 (1969).

All codes and data used to generate the main figures are publicly accessible on GitHub at <https://github.com/ZepengMei/ENSO-prediction> (70).

ACKNOWLEDGMENTS. We acknowledge supports from the National Natural Science Foundation of China (42425101, 41988101, 42505021, 42301058), the Postdoctoral Fellowship Program of China Postdoctoral Science Foundation (GZC20250218), and Fujian Institute for Cross-Straits Integrated Development (LARH24JB07). D.C. is supported by Tsinghua University (100008001).

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- J.-H. Park *et al.*, Significant winter Atlantic Niño effect on ENSO and its future projection. *NPJ Clim. Atmos. Sci.* **7**, 238 (2024).
- Y. Zhao, Y. Jin, A. Capotondi, J. Li, D. Sun, The role of tropical Atlantic in ENSO predictability barrier. *Geophys. Res. Lett.* **50**, e2022GL101853 (2023).
- L. Zhang *et al.*, Emergence of the central Atlantic Niño. *Sci. Adv.* **9**, eadi5507 (2023).
- F.-F. Jin, An equatorial ocean recharge paradigm for ENSO. Part I: Conceptual model. *J. Atmos. Sci.* **54**, 811–829 (1997).
- T. Iwaki, M. Watanabe, Multiyear ENSO dynamics as revealed in observations, climate model simulations, and the linear recharge oscillator. *J. Clim.* **35**, 7625–7642 (2022).
- Y. Tanimoto, S.-P. Xie, Inter-hemispheric decadal variations in SST, surface wind, heat flux and cloud cover over the Atlantic Ocean. *J. Meteorol. Soc. Japan. Ser.* **80**, 1199–1219 (2002).
- M. Collins *et al.*, The impact of global warming on the tropical Pacific Ocean and El Niño. *Nat. Geosci.* **3**, 391–397 (2010).
- C. Bos, T. Delcroix, Observed equatorial Rossby waves and ENSO-related warm water volume changes in the equatorial Pacific Ocean. *J. Geophys. Res. Oceans* **113**, 2007JC004613 (2008).
- K. Y. Kim, Y. Y. Kim, Mechanism of Kelvin and Rossby waves during ENSO events. *Meteorol. Atmos. Phys.* **81**, 169–189 (2002).
- S. Liu, P. Chang, X. Wan, S. G. Yeager, I. Richter, Role of the Maritime Continent in the remote influence of Atlantic Niño on the Pacific. *Nat. Commun.* **14**, 3327 (2023).
- A. J. Clarke, S. Van Gorder, Improving El Niño prediction using a space-time integration of Indo-Pacific winds and equatorial Pacific upper ocean heat content. *Geophys. Res. Lett.* **30**, 2002GL016673 (2003).
- C. S. Meinen, M. J. McPhaden, Observations of warm water volume changes in the equatorial Pacific and their relationship to El Niño and La Niña. *J. Climate* **13**, 3551–3559 (2000).
- C. C. Ibeuchi, M. B. Richman, Deep learning with autoencoders and LSTM for ENSO forecasting. *Clim. Dyn.* **62**, 5683–5697 (2024).
- C. Xiaoqun *et al.*, ENSO prediction based on long short-term memory (LSTM). *IOP Conf. Ser. Mater. Sci. Eng.* **799**, 012035 (2020).
- X. Dong, F. Xue, Phase transition of the Pacific decadal oscillation and decadal variation of the East Asian summer monsoon in the 20th century. *Adv. Atmos. Sci.* **33**, 330–338 (2016).
- S. M. Lundberg, S.-I. Lee, A unified approach to interpreting model predictions. *Adv. Neural Inf. Process. Syst.* **30**, 4768–4777 (2017).
- L. Prechelt, Early stopping, but when? in *Neural Networks: Tricks of the Trade*, G. Montavon, G. B. Orr, K.-R. Müller, Eds. (Springer, Berlin, Heidelberg, 2002), pp. 55–69.
- C. J. Willmott, K. Matsuura, Advantages of the mean absolute error (MAE) over the root mean square error (RMSE) in assessing average model performance. *Clim. Res.* **30**, 79–82 (2005).
- H. Chen, Y. Jin, X. Shen, X. Lin, R. Hu, El Niño and La Niña asymmetry in short-term predictability on springtime initial condition. *NPJ Clim. Atmos. Sci.* **6**, 121 (2023).
- S. H. Im, S. I. An, S. T. Kim, F. F. Jin, Feedback processes responsible for El Niño–La Niña amplitude asymmetry. *Geophys. Res. Lett.* **42**, 5556–5563 (2015).
- S. W. Fang, J. Y. Yu, A control of ENSO transition complexity by tropical Pacific mean SSTs through tropical-subtropical interaction. *Geophys. Res. Lett.* **47**, e2020GL087933 (2020).
- S. W. Fang, J. Y. Yu, Contrasting transition complexity between El Niño and La Niña: Observations and CMIP5/6 models. *Geophys. Res. Lett.* **47**, e2020GL088926 (2020).
- X. Shi *et al.*, Convolutional LSTM network: A machine learning approach for precipitation nowcasting. *Adv. Neural Inf. Process. Syst.* **28**, 802–810 (2015).
- B. Wang *et al.*, Understanding the recent increase in multiyear La Niñas. *Nat. Clim. Change* **13**, 1075–1081 (2023).
- T. Geng *et al.*, Increased occurrences of consecutive La Niña events under global warming. *Nature* **619**, 774–781 (2023).
- W. Cai *et al.*, Increased frequency of extreme La Niña events under greenhouse warming. *Nat. Clim. Change* **5**, 132–137 (2015).
- N. C. Johnson, S.-P. Xie, Changes in the sea surface temperature threshold for tropical convection. *Nat. Geosci.* **3**, 842–845 (2010).
- N. A. Rayner *et al.*, Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *J. Geophys. Res. Atmos.* **108**, 2002JD002670 (2003).

59. J. J. Kennedy, N. A. Rayner, R. O. Smith, D. E. Parker, M. Saunby, Reassessing biases and other uncertainties in sea surface temperature observations measured in situ since 1850: 2. Biases and homogenization. *J. Geophys. Res.* **116**, D14104 (2011).
60. B. Bell *et al.*, The ERA5 global reanalysis: Preliminary extension to 1950. *Q. J. R. Meteorol. Soc.* **147**, 4186–4227 (2021).
61. H.-T. Lee, NOAA Climate Data Record (CDR) of daily outgoing longwave radiation (OLR), Version 2.0. NOAA National Centers for Environmental Information. <https://doi.org/10.25921/9pt5-by77> (2025).
62. R. F. Adler *et al.*, The new version 2.3 of the Global Precipitation Climatology Project (GPCP) monthly analysis product. *Atmosphere (Basel)* **9**, 138 (2018).
63. D. W. Behringer, M. Ji, A. Leetmaa, An improved coupled model for ENSO prediction and implications for ocean initialization. Part I: The ocean data assimilation system. *Mon. Weather Rev.* **126**, 1013–1021 (1998).
64. A. G. Barnston, M. K. Tippett, M. L. L'Heureux, S. Li, D. G. DeWitt, Skill of real-time seasonal ENSO model predictions during 2002–11: Is our capability increasing? *Bull. Am. Meteorol. Soc.* **93**, 631–651 (2012).
65. D. Chen *et al.*, Strong influence of westerly wind bursts on El Niño diversity. *Nat. Geosci.* **8**, 339–345 (2015).
66. B. Huang *et al.*, Improvements of the daily optimum interpolation sea surface temperature (DOISST) version 2.1. *J. Clim.* **34**, 2923–2939 (2021).
67. K. E. Trenberth, The definition of El Niño. *Bull. Am. Meteorol. Soc.* **78**, 2771–2778 (1997).
68. J.-Y. Yu, H.-Y. Kao, T. Lee, S. T. Kim, Subsurface ocean temperature indices for Central-Pacific and Eastern-Pacific types of El Niño and La Niña events. *Theor. Appl. Climatol.* **103**, 337–344 (2011).
69. Y.-G. Ham, J.-H. Kim, J.-J. Luo, Deep learning for multi-year ENSO forecasts. *Nature* **573**, 568–572 (2019).
70. Z. Mei, ZepengMei/ENSO-prediction. GitHub. <https://github.com/ZepengMei/ENSO-prediction>. Accessed 14 October 2025.