

The relation of ENSO with global surface temperature

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Key Points:

- The familiar three-month lag between ENSO and global mean temperature emerges from averaging a seasonally varying relation
- The seasonally varying relation is phase-locked to the annual cycle, strongest in boreal winter, and mostly limited to the tropics
- Delayed tropical warming outside the Pacific sets the timing of the February peak in tropical mean temperature

Abstract

Here we examined the seasonal structure of the El Niño–Southern Oscillation (ENSO)–global surface temperature relation in monthly observations for June 1979–May 2026. Neglecting seasonality, correlations of Niño-3.4 with global mean surface temperature (GMST) and tropical mean surface temperature (TMST) are largest at lags of three and two months, respectively; without detrending, GMST correlations are statistically insignificant. However, this apparent lag emerges from averaging a seasonally varying, phase-locked relation rather than from a season-independent relation. The largest month-dependent correlations of Niño-3.4 with GMST and TMST occur in January and February, respectively, and are related to tropical responses outside of the Pacific, consistent with atmospheric bridge mechanisms. Zonally averaged ENSO composites show temperature signals are mostly limited to the tropics, though global composites show notable exceptions over North America, Asia, and Europe. The space–time structure of the ENSO–temperature relation provides a new target for climate model assessment.

Plain Language Summary

El Niño and La Niña are predictable shifts in tropical Pacific Ocean temperatures that affect temperatures around the world. Earlier studies found that global temperature changes on average a few months after the Pacific does, but that average delay hides an important seasonal pattern. On average, global temperatures react most strongly in January, while the tropics peak a month later in February. We also tracked how temperature changes spread beyond the Pacific during El Niño and La Niña events. Changes are mostly limited to the tropics. By February, tropical temperature changes outside the Pacific match those from the tropical Pacific. These results can help to anticipate when and where El Niño and La Niña events will affect global temperatures.

1 Introduction

Global surface temperatures are steadily increasing due to the accumulation of greenhouse gases in the atmosphere from human activities. At the same time, natural forcings and internal variability drive year-to-year fluctuations about those warming trends. Among the natural influences on global temperature, El Niño/Southern Oscillation (ENSO) is of particular interest because its substantial contribution to global temperature has long been recognized (Angell, 1981) and because it is predictable seasons in advance (L’Heureux

et al., 2020). These two properties make ENSO a leading source of skill in physics-based and statistical forecasts of global mean surface temperature (GMST; Tippett & Becker, 2024, 2026). Thus, a better understanding of the influence of ENSO on global temperature can improve our ability to anticipate short-term global temperature variations and to understand observed variability (Raghuraman et al., 2024; Rantanen & Laaksonen, 2024).

A notable finding in previous studies is the delayed response of global temperatures to ENSO. In an early study, Angell (1981) compared variations of an equatorial eastern Pacific sea surface temperature (SST) index with atmospheric temperature variations from a 63-station global radiosonde network. That work found that tropical tropospheric temperature (0–16 km average), as well as surface temperature, was maximally correlated with the SST index at about a two-season lag. Angell (2000) used this lagged relation to account for variability in global temperatures due to ENSO and thereby improve estimates of temperature trends. Similarly, Lean and Rind (2008) separated forced and natural variability in GMST by fitting GMST in a multiple linear regression that included as predictors an ENSO index lagged by four months, volcanic aerosols, solar irradiance, and anthropogenic forcing. Likewise, Foster and Rahmstorf (2011) fit GMST by a multiple linear regression that included as predictors a standardized ENSO index lagged by two–five months, aerosol optical depth, total solar irradiance, and a linear trend in time. Trenberth et al. (2002) found that the lag correlation between Niño-3.4 and GMST was largest at three to four months and concluded that delayed surface warming outside of the tropical Pacific was due to persistent atmospheric circulation changes forced from the tropical Pacific.

The “atmospheric bridge” perspective introduced in the 1990s provides a physical framework for how ENSO-forced circulation changes drive remote SST responses via changes in radiative and heat fluxes (see Alexander et al., 2002, for a review). In the atmospheric bridge paradigm, the delayed remote response is due to the rapid (on the order of two weeks) atmospheric adjustment to tropical Pacific SST anomalies followed by the slower integration of the resulting flux anomalies by the ocean mixed layer (Klein et al., 1999). The atmospheric bridge responses in the tropics (Indian Ocean, South China Sea, and tropical Atlantic) are especially relevant for GMST because they have the same sign as the tropical Pacific ENSO signal and, thus, contribute constructively to GMST changes.

Although the relation between ENSO and global temperature is well established, some issues related to the seasonality of the relation remain to be explored fully. For instance, there is a gap between atmospheric bridge studies that center their analysis on the boreal winter ENSO peak and GMST studies that examine lag correlations with all months pooled together. Thus, it remains unclear to what extent the three-to-four-month lag correlation between ENSO and GMST (e.g., Trenberth et al., 2002; Lean & Rind, 2008; Foster & Rahmstorf, 2011) holds throughout the year or is the average of a seasonally varying relation. Similarly, atmospheric bridge studies have left open the question of whether the same mechanisms connecting boreal winter Pacific forcing and remote SST also operate at other times of the year. In addition to the issue of seasonality, increased length and quality of the observational record may allow more robust conclusions than were previously possible. However, with a longer data record, accounting for the upward trend in GMST that has been more apparent since the 1980s may be more important than was the case in previous work.

We address some of these gaps here. We computed lag correlations between Niño-3.4 and GMST with all months pooled and examined the impact of detrending. We addressed seasonality in the relation of ENSO with global temperature by computing month-dependent lag correlations. We examined seasonality in the spatial expression of the ENSO–global temperature relation through time-varying zonal mean, tropical mean, and global ENSO composites. Data and methods are described in Section 2. Results are presented in Section 3. A summary and conclusions are given in Section 4.

2 Data and methods

Our analysis used monthly data for June 1979–May 2026. The Niño-3.4 index is the average SST in the tropical Pacific box 170°W–120°W, 5°S–5°N (Barnston et al., 1997) and was computed from ERSSTv5 (Huang et al., 2017a). For surface temperature, we used the NOAA global surface temperature version 6.1 (NOAA GlobalTemp; Huang et al., 2022) at 5°×5° resolution. Tropical mean surface temperature (TMST) was computed as the average over 22.5°S–22.5°N. The tropical regions used in the analysis are shown in Fig. S1.

Monthly anomalies were computed with respect to the full period. Data were detrended by removing full-period linear trends (all months pooled). The temperature ten-

dency is the change from the previous month. Warm and cool ENSO composites were based on the December–February NOAA Oceanic Niño Index (ONI, version 6) conditions. Warm ENSO years (denoted by the December year) are 1979, 1982, 1986, 1987, 1991, 1994, 1997, 2002, 2004, 2006, 2009, 2014, 2015, 2018, 2019, and 2023. Cool ENSO years are 1983, 1984, 1988, 1995, 1998, 1999, 2000, 2005, 2007, 2008, 2010, 2011, 2017, 2020, 2021, and 2022. Composites were formed over a 16-month window beginning in June (year 0) prior to the boreal winter ENSO peak and extending through September of the following year (year +1). For instance, the 1997/98 El Niño event corresponds to the window June 1997 through September 1998.

Lag correlations $C(L)$ were computed as the correlation between X_t and Y_{t+L} , where L denotes the lag in months, $L = 0, \dots, 16$. Here, X_t and Y_t represent, for example, the Niño-3.4 index and GMST at month t . The month-dependent lag correlation $C(M, L)$ is the correlation between X_t and Y_{t+L} computed using only the months t that fall in base calendar month M ($M = 1, \dots, 12$), so that each year contributes one (X_t, Y_{t+L}) pair. For instance, $C(12, 2)$ is the correlation between December Niño-3.4 and GMST in the following February. $C(M, L)$ was plotted as a function of the target calendar month $M + L$.

The statistical significance of lag correlations was assessed using block bootstrap resampling (12-month June–May blocks; 1000 samples) to account for serial correlation. Standard bootstrap resampling was used for tendencies because no serial correlation was evident. The statistical significance of ENSO composite anomalies was assessed using a permutation test (1000 samples). For global composites, p -values were adjusted for multiple comparisons using the Benjamini–Hochberg false discovery rate (BH-FDR) procedure at $\alpha = 0.15$, and we reported the largest p -value of the points passing the BH-FDR procedure.

3 Results

Correlations of Niño-3.4 with GMST and TMST are largest at lags of three and two months, respectively (Fig. 1a). When trends are not removed, none of the lag correlations of Niño-3.4 with GMST are statistically significant (5% level). In contrast, statistically significant lag correlations of Niño-3.4 with TMST extend to a lag of nine months. Detrending increases the lag correlations substantially—the GMST correlation with Niño-

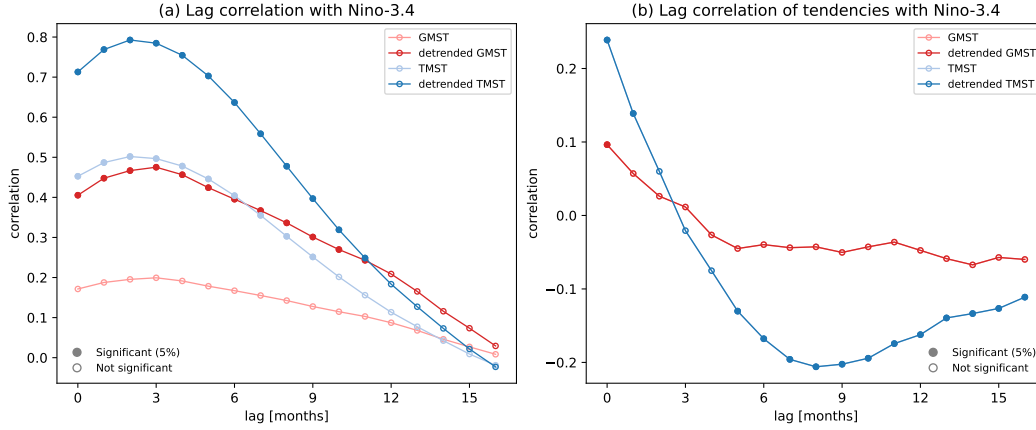


Figure 1. Lag correlation of Niño-3.4 with (a) global and tropical mean surface temperature (GMST and TMST) and (b) GMST and TMST tendencies. Filled circles indicate statistical significance at the 5% level. Results for detrended time series are shown in dark colors.

3.4 at a three-month lag increases from 0.20 to 0.48, and the TMST correlation with Niño-3.4 at a two-month lag increases from 0.50 to 0.79. Niño-3.4 is significantly correlated with GMST tendencies only at zero lag and with TMST tendencies only at lags zero and one (Fig. 1b), which is consistent with the atmospheric bridge paradigm of radiative and heat fluxes responding quickly to circulation anomalies (Klein et al., 1999). The tendency lag correlations for detrended and raw data are indistinguishable because differencing the data effectively detrends it. Spatially averaged correlations show the same time-lag structure. Area-weighted global averages of the gridpoint correlation peak at a lag of three months for detrended temperatures (Fig. S2) and at zero lag for temperature tendencies (Fig. S3).

Month-dependent lag correlations of Niño-3.4 with GMST and TMST are phase locked to the annual cycle and are strongest for target months during boreal fall and winter (Fig. 2). Peak lag correlations for June–January base months are larger than those in Fig. 1a (no detrending). For June–February base months, peak correlations with Niño-3.4 are larger for longer lags, which is explained by the high persistence of Niño-3.4 during this time of the year and the increase in variance as base months move into boreal winter. Detrending increases lag correlation values and extends statistical significance while maintaining much of the overall seasonality structure (Fig. S4). Averaging the month-

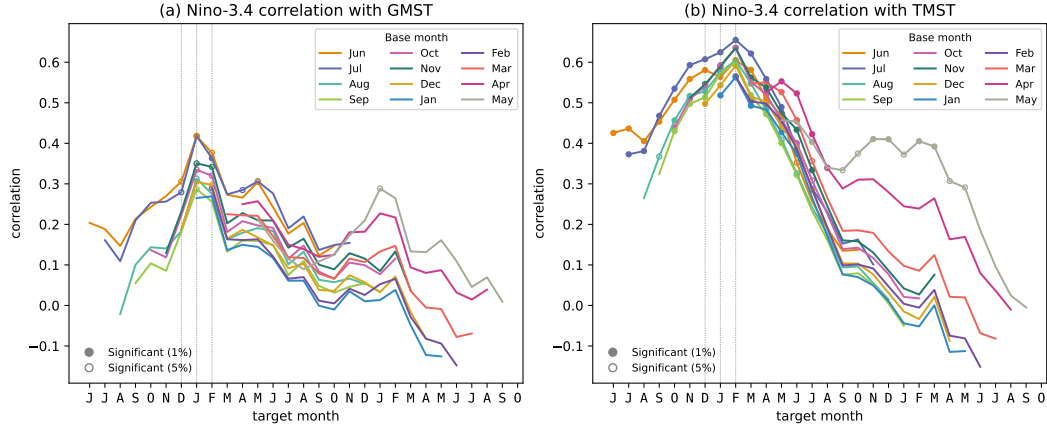


Figure 2. Month-dependent lag correlations of Niño-3.4 with (a) global mean surface temperature (GMST) and (b) tropical mean surface temperature (TMST). The x-axis shows the target month (base month plus lag), and each line corresponds to a different base month (June–May) and spans 16 months. Open and filled dots indicate statistical significance at the 5% and 1% levels, respectively. Vertical dotted lines mark the target months December–February.

dependent lag correlations over base months approximately recovers the all-months lag correlations (Fig. S5).

Statistically significant lag correlations between Niño-3.4 and GMST are mostly limited to January and February target months and peak in January for June–December base months (Fig. 2a). For June–February base months, correlations of Niño-3.4 with TMST peak in February (Fig. 2b), with values that are larger than the ones in Fig. 1a, where all months are pooled together (month-dependent correlations with detrended data are similar but stronger; see Fig. S4). Statistically significant lag correlations between Niño-3.4 and TMST extend into the boreal summer following the ENSO peak. For March–May base months, lag correlations of Niño-3.4 with GMST and TMST mostly decay with increasing lag as they pass through the boreal spring persistence barrier. For both GMST and TMST, lag correlations with Niño-3.4 for the May base month show slight rebounds in the following boreal winter but are substantially lower than those with a June base month, which reflects that May is only marginally past the boreal spring persistence barrier (Torrence & Webster, 1998).

To identify the sources of seasonality in the month-dependent relations with GMST, we computed warm and cool ENSO composites of detrended zonal-mean surface tem-

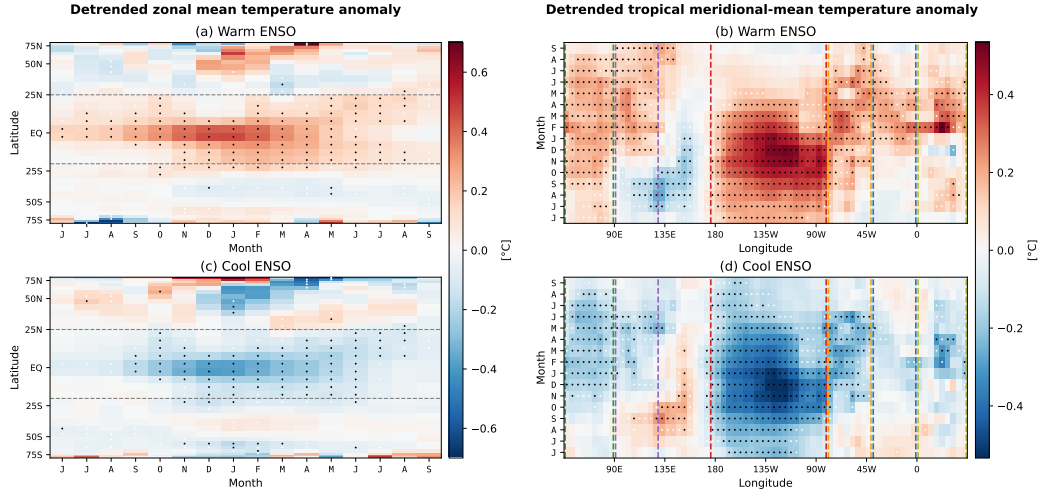


Figure 3. Composites of (a, c) zonal (sinusoidal spacing in latitude) and (b, d) tropical meridional-mean surface temperature anomalies from June (year 0) through September (year +1) during warm and cool ENSO years. White and black dots indicate statistical significance at the 5% and 1% levels, respectively. Dashed lines in panels b and d show Indian (green), South China Sea (purple), tropical Pacific (red), South America (orange), tropical Atlantic (blue), and Africa (olive) regional boundaries.

perature anomalies (Figs. 3a, c) over a 16-month window spanning the ENSO development and decay life cycle. For the most part, statistically significant zonal-mean anomalies are concentrated in the tropics, with only scattered significant anomalies at extratropical latitudes. Early in the ENSO cycle, statistically significant zonal-mean anomalies are concentrated near the equator. Beginning in November, they extend southward to about 20°S, where they persist through July, while their northward extent reaches about 20°N briefly in October and again in February. The broad February signal, which remains fairly strong near the equator and extends farther northward than in December and January, is consistent with the peak correlation of TMST and Niño-3.4 that occurs in February. Near-equatorial anomalies fade by May/June following the boreal winter peak as the ENSO cycle ends. Off-equatorial tropical anomalies persist longer, especially in the warm ENSO composites.

Tropical meridional mean composites (Figs. 3b, d) decompose by longitude the tropical zonal mean signals (Figs. 3a, c). The dominant ENSO signal in tropical meridional mean surface temperature is the expected direct one in the central-eastern tropical Pa-

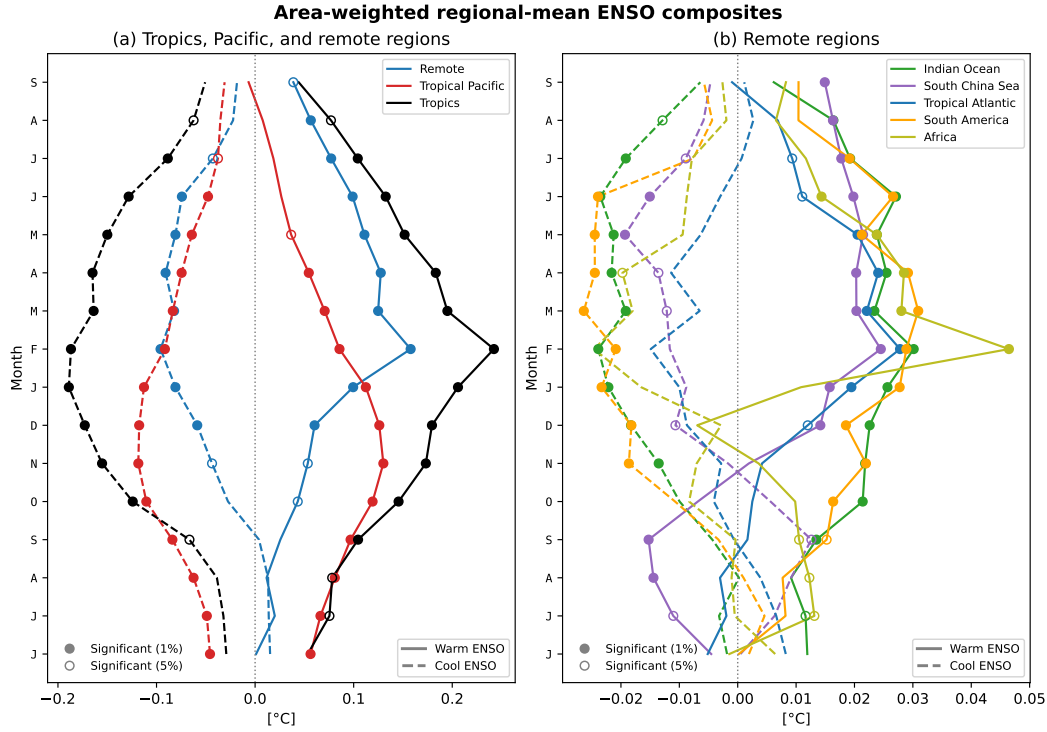


Figure 4. Area-weighted regional mean composites of temperature as a function of month for (a) the tropics, tropical Pacific, and all remote regions combined, and (b) the five remote regions. Open and filled dots indicate statistical significance at the 5% and 1% levels, respectively. See Fig. S1 for region domains.

cific, where it persists for nearly 12 months. Significant anomalies in the Indian region appear in late boreal fall (October/November) and persist for nearly a year. In the South China Sea region, warm ENSO anomalies last from December to September, while cool ENSO anomalies are shorter-lived and more spatially limited. South American regional anomalies are widespread by November and last until the following June, with warm-phase anomalies lasting longer than the cool-phase ones. In the tropical Atlantic, the warm-phase signal has a broad longitudinal extent in February that persists for several months, while the cool-phase signal is mostly not statistically significant. Warm ENSO anomalies in the tropical Atlantic region expand eastward into Africa in February, at the same time as anomalies in the Indian and South China Sea regions have their maximum longitudinal extent.

To quantify when and how much remote regions contribute to tropical mean anomalies, we computed area-weighted regional mean composites (Fig. 4). Warm ENSO TMST

composites peak in February, while cool ones show a less well-defined peak in January–February (Fig. 4a). We find that surface temperatures outside the tropical Pacific are responsible for the timing of the TMST peak. Early in the ENSO cycle (June–September), nearly all tropical surface temperature anomalies come from the tropical Pacific. However, as tropical Pacific anomalies peak in November/December and decay, the contribution of remote regions grows, matches the tropical Pacific contribution, and peaks in February. The February peak in remote regions is more pronounced for warm ENSO events than for cool ones. The warm ENSO temperature composites for all remote regions peak in February, except for South America, which peaks in March (Fig. 4b). Tropical Atlantic and South China Sea anomalies develop later than those in other regions, especially for cool events, although the values for cool events are largely not statistically significant in these two regions. Contributions of remote regions to the warm ENSO peak in February are roughly comparable across regions except for Africa, where large values reflect the broad extent of the warm anomalies previously noted in Fig. 3b.

Although zonal mean ENSO-related temperature anomalies are mostly confined to the tropics, some prominent signals appear outside of the tropics (Fig. 5). During warm ENSO, strong warm anomalies are present in December over western and central Canada, extending into portions of Alaska and the northern Midwestern US. Also during warm ENSO, positive temperature anomalies are present over Southern Africa in December–April, extending northward and into East Africa in February–April; an approximately opposite pattern is present during cool ENSO. In November of warm ENSO years, positive anomalies span much of Central Europe, while December warming is weaker and limited to parts of Germany and Poland (see Fig. S6 for a zoom). During cool ENSO, significant negative anomalies appear on the west coast of North America in December, February, and March; a broad region of negative anomalies covers the interior of Asia; and positive anomalies are centered over the Arctic Ocean. Australia exhibits sporadic anomalies that are positive during El Niño and negative during La Niña conditions.

4 Summary and conclusions

The influence of ENSO on global mean surface temperature (GMST) is substantial and predictable. Short-term ENSO-related changes in GMST (0.1–0.2°C per event; Tippett & Becker, 2026) are comparable in magnitude to a decade or more of the long-term trend ($\sim 0.2^\circ\text{C decade}^{-1}$; IPCC, 2021) and can be forecast seasons in advance. Here,

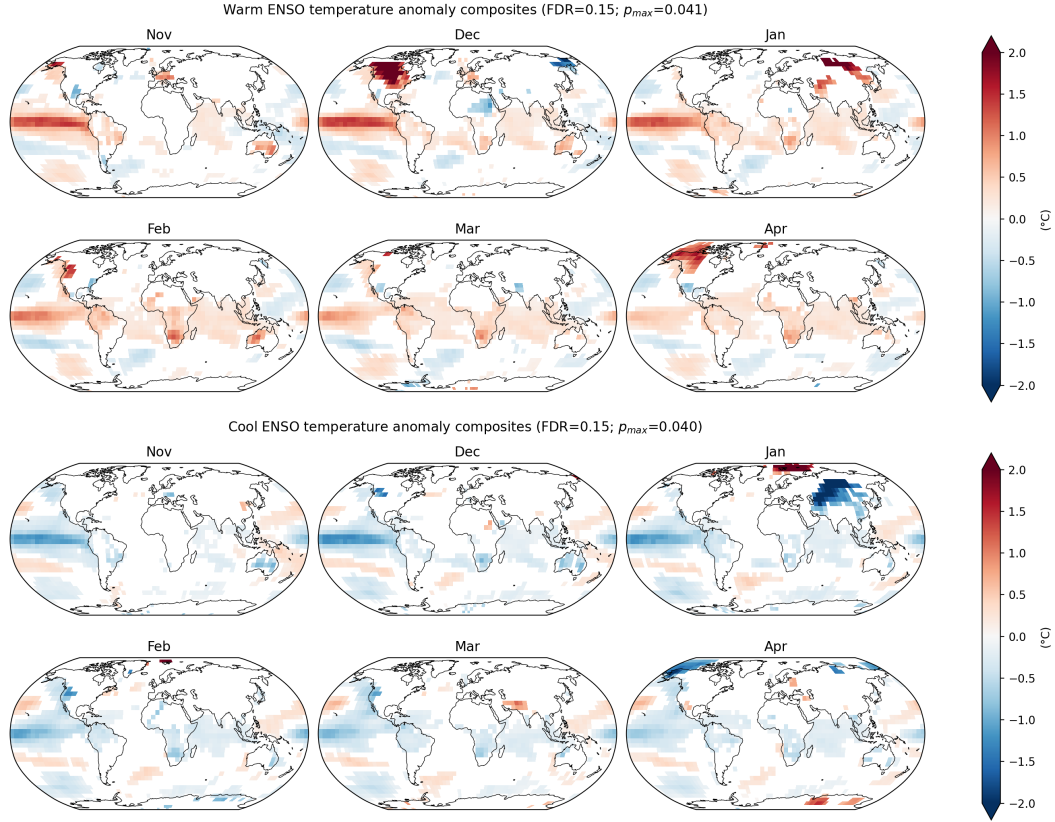


Figure 5. Warm ENSO (top two rows) and cool ENSO (bottom two rows) composites of detrended surface temperature anomalies for November–April. Shading indicates statistically significant anomalies after BH-FDR control (all six maps per phase together) at the 15% level; p_{max} is the largest p-value passing BH-FDR control.

we build on prior studies by explicitly examining detrended temperatures, comparing the Niño-3.4 relation to both global and tropical mean surface temperatures (TMST), and analyzing the seasonality of the relation and the spread of heating anomalies across the globe.

When all months are pooled, we find that the correlation between Niño-3.4 and GMST maximizes at a three-month lag (Fig. 1), similar to the results of Trenberth et al. (2002). That study, using data for 1950–1998, found an overall stronger correlation than we find for 1979–2026. We find similar results to theirs for the common period (1979–1998), and correlations for 1999–2026 are substantially lower (not shown). The stronger trend in GMST over the more recent period 1999–2026 results in ENSO explaining less variance and likely accounts for the overall weaker correlation found here. Linearly removing long-term climate change trends from the data leaves the ENSO relation as the primary signal and substantially increases the correlation. We also find that Niño-3.4 has a much stronger relation to TMST than to the global mean, with the detrended Niño-3.4 explaining about 60% of the variance of detrended TMST months later. The tendency of GMST, that is, the month-to-month change, is significantly correlated with Niño-3.4 at zero lag only, which is consistent with the atmospheric bridge and the timescale of Rossby wave development and propagation.

Month-dependent lag correlations are an effective tool for diagnosing seasonality (DelSole et al., 2026) and have been used extensively in ENSO studies to quantify the spring persistence/predictability barrier (Liu et al., 2018; Tian et al., 2019; Tippett & L’Heureux, 2020; Torrence & Webster, 1998). Here month-dependent lag correlations show that the relations of Niño-3.4 with GMST and TMST are phase-locked to the annual cycle and strongest for target months during boreal fall and winter (Fig. 2). This temporal correlation structure means that lag correlations are primarily a function of target month rather than lag. Averaging the month-dependent lag correlations over base months recovers the oft-cited result that GMST lags Niño-3.4 by about three months, demonstrating that this apparent lag emerges from averaging over a seasonally varying, phase-locked mechanism rather than from a season-independent lag operating throughout the year.

ENSO life cycle composites show that statistically significant zonal mean surface temperature anomalies are mostly confined to the tropics (Fig. 3a). ENSO-related trop-

ical meridional mean temperature anomalies outside the tropical Pacific emerge at different times in the ENSO cycle, consistent with atmospheric bridge mechanisms, and in-phase anomalies cover nearly the entire tropical band in January/February/March (Fig. 3b). Regional composites show that during warm ENSO events, tropical regions outside of the Pacific do not contribute significantly to TMST until October; by February, the average anomaly in the remote regions is nearly twice that in the tropical Pacific (Fig. 4a). This feature appears to explain the February peak in the month-dependent lag correlations. For cool ENSO, it is November before the remote tropical anomaly is significant, and the anomaly in remote regions approximately matches that of the Pacific. Thus, although tropical Pacific anomalies are present from June onward, significant remote tropical anomalies appear only in boreal fall and winter, which suggests that the atmospheric bridge mechanisms connecting the tropical Pacific to remote regions operate mainly in those seasons rather than throughout the year.

Outside the tropics, there are some well-known temperature signals in the higher latitudes (Halpert & Ropelewski, 1992), including a strong warm anomaly during El Niño in December over North America (Becker & Tippett, 2024; Ropelewski & Halpert, 1986; Tippett et al., 2026) and a cool anomaly over interior Asia in January during La Niña (Luo et al., 2021), as seen in Fig. 5. The warm anomalies over Europe in November and, to a lesser extent, December are consistent with the documented early-winter ENSO teleconnection to the North Atlantic–European sector (King et al., 2018). The zonal mean composites suggest poleward propagation of temperature anomalies in the northern extratropics throughout the winter and spring, although these anomalies are not statistically significant.

The distinctive space–time structure of the ENSO temperature response (e.g., Fig. 3) suggests directions for future work. First, the extent to which climate models reproduce the observed seasonal evolution and spatial structure of these anomalies, including their zonal and meridional mean patterns, remains to be assessed. Such comparisons could help identify which aspects of ENSO teleconnections are robustly represented and which are not. Second, whether and how these patterns change in a warming climate could be examined in climate projections (McGregor et al., 2022).

Open Research Section

NOAAGlobalTemp version 6.1 data are available from Huang et al. (2026) at <https://www.ncei.noaa.gov/products/land-based-station/noaa-global-temp>. NOAA Extended Reconstructed SST V5 (ERSSTv5) data are available from Huang et al. (2017b). Seasonal values of the Oceanic Niño Index are available from NOAA Climate Prediction Center (2026).

Conflict of Interest

The authors declare no conflicts of interest.

Acknowledgments

We thank Michelle L. L’Heureux for helpful discussions and suggestions. EJB acknowledges support from NSF (2223262). The authors also acknowledge the use of AI tools, including OpenAI’s ChatGPT and Anthropic’s Claude, to assist with code and manuscript editing.

References

- Alexander, M. A., Bladé, I., Newman, M., Lanzante, J. R., Lau, N.-C., & Scott, J. D. (2002). The atmospheric bridge: The influence of ENSO teleconnections on air—sea interaction over the global oceans. *Journal of Climate*, *15*, 2205–2231. doi: 10.1175/1520-0442(2002)015<2205:TABTIO>2.0.CO;2
- Angell, J. K. (1981). Comparison of variations in atmospheric quantities with sea surface temperature variations in the equatorial eastern Pacific. *Monthly Weather Review*, *109*, 230–243. doi: 10.1175/1520-0493(1981)109<0230:COVIAQ>2.0.CO;2
- Angell, J. K. (2000). Tropospheric temperature variations adjusted for El Niño, 1958–1998. *Journal of Geophysical Research: Atmospheres*, *105*, 11841–11849. doi: 10.1029/2000JD900044
- Barnston, A. G., Chelliah, M., & Goldenberg, S. B. (1997). Documentation of a highly ENSO-related SST region in the equatorial Pacific. *Atmosphere-Ocean*, *35*, 367–383. doi: 10.1080/07055900.1997.9649597
- Becker, E. J., & Tippett, M. K. (2024). Impact of ENSO and trends on the distribution of North American wintertime daily temperature. *Journal of Climate*, *37*,

- 325 3509-3520. doi: 10.1175/JCLI-D-23-0569.1
- 326 DelSole, T., Buckley, M. W., & Tippet, M. K. (2026). Detecting month-dependent
327 predictability with periodic autoregressive models: Reemergence and pre-
328 dictability barriers. *Journal of Climate*. (Submitted)
- 329 Foster, G., & Rahmstorf, S. (2011). Global temperature evolution 1979–2010. *Envi-*
330 *ronmental Research Letters*, 6, 044022. doi: 10.1088/1748-9326/6/4/044022
- 331 Halpert, M. S., & Ropelewski, C. F. (1992). Surface temperature patterns associated
332 with the Southern Oscillation. *Journal of Climate*, 5, 577–593. doi: 10.1175/
333 1520-0442(1992)005<0577:STPAWT>2.0.CO;2
- 334 Huang, B., Thorne, P. W., Banzon, V. F., Boyer, T., Chepurin, G., Lawrimore,
335 J. H., ... Zhang, H.-M. (2017a). Extended reconstructed sea surface tem-
336 perature, version 5 (ERSSTv5): Upgrades, validations, and intercomparisons.
337 *Journal of Climate*, 30, 8179–8205. doi: 10.1175/JCLI-D-16-0836.1
- 338 Huang, B., Thorne, P. W., Banzon, V. F., Boyer, T., Chepurin, G., Lawrimore,
339 J. H., ... Zhang, H.-M. (2017b). NOAA Extended Reconstructed Sea Sur-
340 face Temperature (ERSST), Version 5 [Dataset]. NOAA National Centers for
341 Environmental Information. doi: 10.7289/V5T72FNM
- 342 Huang, B., Yin, X., Menne, M. J., Vose, R., & Zhang, H.-M. (2022). Improvements
343 to the land surface air temperature reconstruction in NOAA GlobalTemp: An
344 artificial neural network approach. *Artificial Intelligence for the Earth Sys-*
345 *tems*, 1, e220032. doi: 10.1175/AIES-D-22-0032.1
- 346 Huang, B., Yin, X., Menne, M. J., & Vose, R. S. (2026). NOAA Global Surface
347 Temperature Dataset (NOAA GlobalTemp), Version 6.1 [Dataset]. NOAA Na-
348 tional Centers for Environmental Information.
- 349 IPCC. (2021). *Climate Change 2021: The Physical Science Basis. Contribution*
350 *of Working Group I to the Sixth Assessment Report of the Intergovernmental*
351 *Panel on Climate Change* (V. Masson-Delmotte et al., Eds.). Cambridge,
352 United Kingdom and New York, NY, USA: Cambridge University Press. doi:
353 10.1017/9781009157896
- 354 King, M. P., Herceg-Bulić, I., Bladé, I., García-Serrano, J., Keenlyside, N.,
355 Kucharski, F., ... Sobolowski, S. (2018). Importance of late fall ENSO tele-
356 connection in the Euro-Atlantic sector. *Bulletin of the American Meteorological*
357 *Society*, 99, 1337–1343. doi: 10.1175/BAMS-D-17-0020.1

- 358 Klein, S. A., Soden, B. J., & Lau, N.-C. (1999). Remote sea surface temperature
359 variations during ENSO: Evidence for a tropical atmospheric bridge. *Journal*
360 *of Climate*, *12*, 917–932. doi: 10.1175/1520-0442(1999)012<0917:RSSTVD>2.0
361 .CO;2
- 362 Lean, J. L., & Rind, D. H. (2008). How natural and anthropogenic influences alter
363 global and regional surface temperatures: 1889 to 2006. *Geophysical Research*
364 *Letters*, *35*. doi: 10.1029/2008GL034864
- 365 L’Heureux, M. L., Levine, A., Newman, M., Ganter, C., Luo, J.-J., Tippett, M. K.,
366 & Stockdale, T. (2020). ENSO Prediction. In M. McPhaden, A. Santoso, &
367 W. Cai (Eds.), *El Niño-Southern Oscillation (ENSO) in a Changing Climate*.
368 AGU. doi: 10.1002/9781119548164.ch10
- 369 Liu, Z., Jin, Y., & Rong, X. (2018, 2019/09/17). A theory for the seasonal pre-
370 dictability barrier: Threshold, timing, and intensity. *J. Climate*, *32*, 423–443.
371 doi: 10.1175/JCLI-D-18-0383.1
- 372 Luo, B., Luo, D., Dai, A., Simmonds, I., & Wu, L. (2021). A connection of winter
373 Eurasian cold anomaly to the modulation of Ural blocking by ENSO. *Geophys-*
374 *ical Research Letters*, *48*, e2021GL094304. doi: 10.1029/2021GL094304
- 375 McGregor, S., Cassou, C., Kosaka, Y., & Phillips, A. S. (2022). Projected
376 ENSO teleconnection changes in CMIP6. *Geophysical Research Letters*, *49*,
377 e2021GL097511. doi: 10.1029/2021GL097511
- 378 NOAA Climate Prediction Center. (2026). Seasonal Oceanic Niño Index
379 [Dataset]. Retrieved from [https://www.cpc.ncep.noaa.gov/data/indices/](https://www.cpc.ncep.noaa.gov/data/indices/oni.ascii.txt)
380 [oni.ascii.txt](https://www.cpc.ncep.noaa.gov/data/indices/oni.ascii.txt)
- 381 Raghuraman, S. P., Soden, B., Clement, A., Vecchi, G., Menemenlis, S., & Yang,
382 W. (2024). The 2023 global warming spike was driven by the El Niño–
383 Southern Oscillation. *Atmospheric chemistry and physics*, *24*, 11275–11283.
384 doi: 10.5194/acp-24-11275-2024
- 385 Rantanen, M., & Laaksonen, A. (2024). The jump in global temperatures in Septem-
386 ber 2023 is extremely unlikely due to internal climate variability alone. *npj Cli-*
387 *mate and Atmospheric Science*, *7*, 34. doi: 10.1038/s41612-024-00582-9
- 388 Ropelewski, C. F., & Halpert, M. S. (1986). North American precipitation
389 and temperature patterns associated with the El Niño/Southern Oscilla-
390 tion (ENSO). *Monthly Weather Review*, *114*, 2352–2362. doi: 10.1175/

- 1520-0493(1986)114(2352:NAPATP)2.0.CO;2
- Tian, B., Ren, H.-L., Jin, F.-F., & Stuecker, M. F. (2019). Diagnosing the representation and causes of the ENSO persistence barrier in CMIP5 simulations. *Clim. Dyn.*, 53, 2147–2160. doi: 10.1007/s00382-019-04810-4
- Tippett, M. K., & Becker, E. J. (2024). Trends, skill, and sources of skill in initialized climate forecasts of global mean temperature. *Geophysical Research Letters*, 51, e2024GL110703. doi: <https://doi.org/10.1029/2024GL110703>
- Tippett, M. K., & Becker, E. J. (2026). ENSO-conditioned evolution of global mean surface temperature. *Geophysical Research Letters*, 53, e2026GL124175. doi: 10.1029/2026GL124175
- Tippett, M. K., Becker, E. J., Lee, S. H., & L’Heureux, M. L. (2026). ENSO, weather regimes, and U.S. heating degree days. *Weather and Forecasting*. (submitted) doi: 10.31223/X5ZJ6W
- Tippett, M. K., & L’Heureux, M. L. (2020). Low-dimensional representations of Niño 3.4 evolution and the spring persistence barrier. *npj Climate and Atmospheric Science*, 3, 24. doi: 10.1038/s41612-020-0128-y
- Torrence, C., & Webster, P. J. (1998). The annual cycle of persistence in the El Niño/Southern Oscillation. *Quart. J. Roy. Meteor. Soc.*, 124, 1985–2004.
- Trenberth, K. E., Caron, J. M., Stepaniak, D. P., & Worley, S. (2002). Evolution of El Niño–Southern Oscillation and global atmospheric surface temperatures. *Journal of Geophysical Research: Atmospheres*, 107, AAC–5. doi: 10.1029/2000JD000298

413 **Supporting Information for “The relation of ENSO with global sur-**
414 **face temperature”**

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420 **Contents of this file**

421 1. Figures S1 to S6

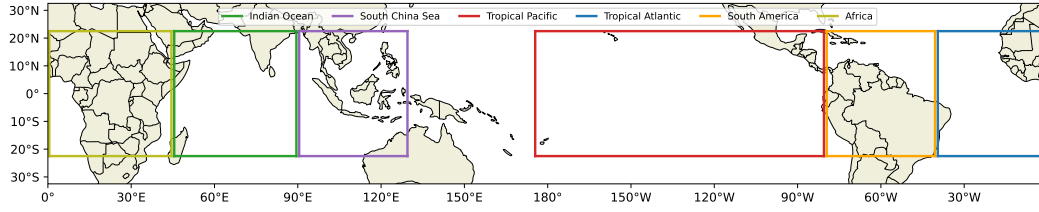


Figure S1. The tropical regions used in the composite analysis.

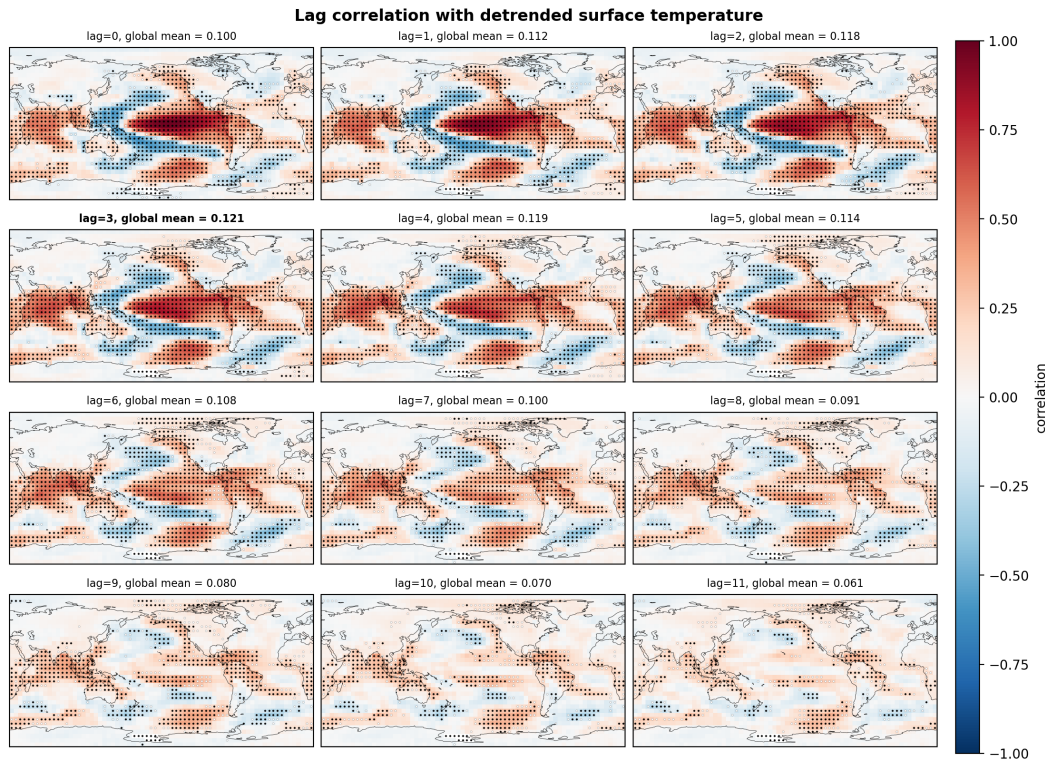


Figure S2. Lag correlation (all months) of Niño-3.4 with detrended surface temperature.

White and black dots indicate statistical significance at the 5% and 1% levels, respectively. The area-weighted global mean of the correlation is shown in the title, with the lag of maximum value in bold.

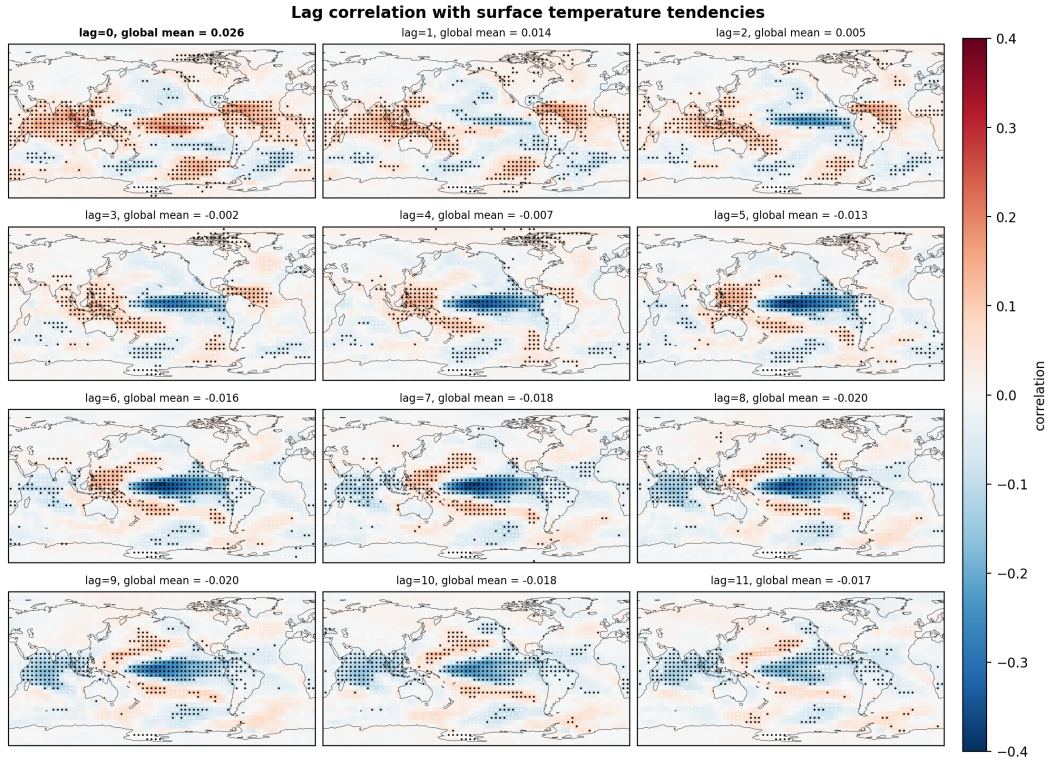


Figure S3. Lag correlation (all months) of Niño-3.4 with surface temperature **tendencies**. White and black dots indicate statistical significance at the 5% and 1% levels, respectively. The area-weighted global mean of the correlation is shown in the title, with the lag of maximum value in bold.

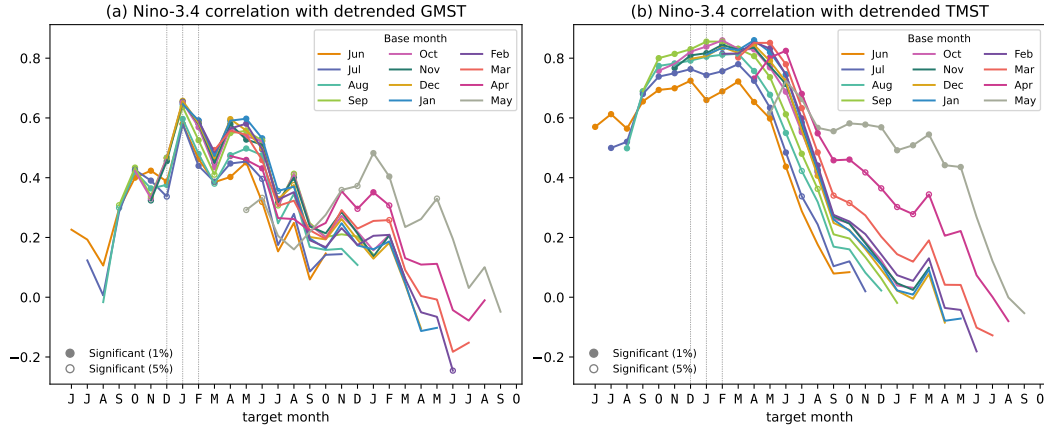


Figure S4. Month-dependent lag correlations of Niño-3.4 with (a) detrended global mean surface temperature (GMST) and (b) detrended tropical mean surface temperature (TMST). The x-axis shows the target month (base month plus lag), and each line corresponds to a different base month (June–May) and extends 16 months. Open and filled dots indicate statistical significance at the 5% and 1% levels, respectively. Vertical dotted lines mark the target months December–February.

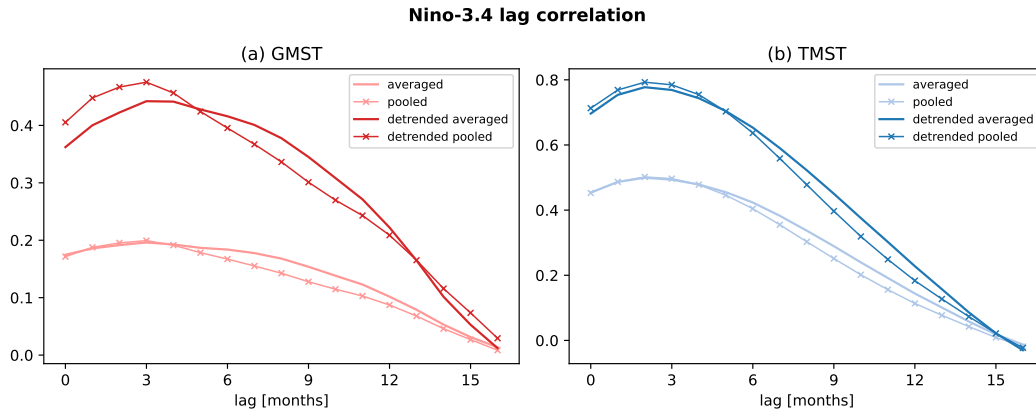


Figure S5. Lag correlations (all months) and averages of month-dependent lag correlations of Niño-3.4 with (a) global mean surface temperature (GMST) and (b) tropical mean surface temperature (TMST). Dark (light) colors show detrended (undetrended) results.

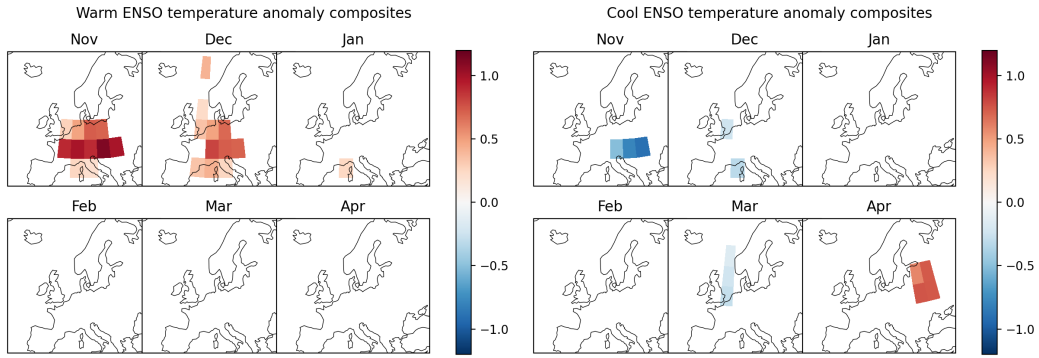


Figure S6. As in Fig. 5 but zoomed in on Europe. Warm ENSO (left) and cool ENSO (right) composites of detrended surface temperature anomalies for November–April. Shading indicates statistically significant anomalies after BH-FDR control applied to the global map (all six maps per phase together) at the 15% level.