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Key Points:

- Tropical-mean radiative anomalies are 90° out of phase with the El Niño–Southern Oscillation (ENSO) cycle
- These radiative anomalies reflect a sea surface temperature (SST) “pattern effect” associated with the growth and decay of ENSO
- The findings are suggestive of a two-way coupling between SST variability and the radiation budget

Supporting Information:

Supporting Information may be found in the online version of this article.

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The El Niño–Southern Oscillation Pattern Effect

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Abstract El Niño–Southern Oscillation (ENSO) variability is accompanied by out-of-phase anomalies in the top-of-atmosphere tropical radiation budget, with anomalous downward flux (i.e., net radiative heating) before El Niño and anomalous upward flux thereafter (and vice versa for La Niña). Here, we show that these radiative anomalies result mainly from a sea surface temperature (SST) “pattern effect,” mediated by changes in tropical-mean tropospheric stability. These stability changes are caused by SST anomalies migrating from climatologically cool to warm regions over the ENSO cycle. Our results are suggestive of a two-way coupling between SST variability and radiation, where ENSO-induced radiative changes may in turn feed back onto SST during ENSO.

Plain Language Summary Predicting long-term climate change requires understanding how and why the Earth’s radiation budget varies on short timescales. Natural climate variability on such timescales is dominated by the El Niño–Southern Oscillation (ENSO) phenomenon, involving large changes in sea surface temperature (SST) in the tropical Pacific. Here, we show that the evolution of the tropical radiation budget during ENSO events is dictated by the location of the SST anomalies, which migrate from colder regions to warmer regions. This change in the spatial distribution of SSTs affects the temperature at higher levels in the atmosphere, which in turn changes the amount of low cloud and thereby the tropical radiation budget. These relationships are suggestive of a two-way coupling between ENSO SST changes and radiation.

1. Introduction

In the context of rapid anthropogenic climate change, a pressing research question is to understand the physical processes controlling the global radiation budget. Predicting the long-term forced radiative response requires knowledge of the mechanisms driving natural unforced radiative variability (Colman & Hanson, 2017; Gregory & Andrews, 2016; Gregory et al., 2020). On decadal scales, climate model simulations suggest that historical variations in the radiation budget were caused in large part by varying sea surface temperature (SST) patterns, through their impact on low-cloud amount (Andrews et al., 2018; Zhou et al., 2016)—the so-called “SST pattern effect” (Stevens et al., 2016)—though questions remain regarding the reliability of SST reconstructions (Flannaghan et al., 2014; Fueglistaler & Silvers, 2021; Lewis & Mauritsen, 2021).

For the present study, we define the “pattern effect” as the component of the SST-driven radiative response that deviates from the response expected from near-uniform warming. While this pattern effect has generally been studied in the context of multidecadal climate variations in previous literature (e.g., Andrews et al., 2015; Ceppi & Gregory, 2017; Gregory & Andrews, 2016; Proistosescu & Huybers, 2017), here we consider its possible relevance to radiative variability on shorter, monthly to interannual timescales, where natural variability is largest (Lutsko & Takahashi, 2018).

On such timescales, the El Niño–Southern Oscillation (ENSO) constitutes the dominant mode of coupled ocean-atmosphere variability. In the atmosphere, ENSO is associated with large regional anomalies in tropical temperature and circulation, accompanied by changes in cloud properties and the top-of-atmosphere radiation budget (Klein et al., 1999; Loeb et al., 2012; Middlemas et al., 2019; Park & Leovy, 2004; Rädel et al., 2016; Radley et al., 2014; Trenberth et al., 2002). Our focus here is on the smaller tropical-mean radiative anomalies that occur during ENSO, as a residual of the much larger regional changes, and which are out of phase relative to ENSO-driven temperature anomalies: lead-lag relationships reveal a net input of

radiative energy before an El Niño event, followed by radiative cooling thereafter (Fueglistaler, 2019; Kolly & Huang, 2018; Lutsko, 2018; Lutsko & Takahashi, 2018; Xie et al., 2016). Previous literature has interpreted these out-of-phase radiative anomalies either as being SST-driven (Lutsko & Takahashi, 2018), or as being internal to the atmosphere, thus reflecting stochastic one-way forcing from the atmosphere on SSTs (Xie et al., 2016).

Here, we show that the tropical-mean radiative anomalies during the ENSO cycle are in fact driven by an SST pattern effect associated with the growth and decay phases of ENSO. Our results are therefore suggestive of a two-way coupling between ENSO and the radiative budget, where the ENSO SST patterns modify clouds and radiation, and these may in turn force tropical SST during ENSO. Note that we define the radiative “forcing” of ENSO in a broad sense: we do not investigate the radiative contribution to SST anomalies in the Niño-3.4 region specifically, but only the impact of radiation on ENSO anomalies in the tropical-mean energy budget. Our findings suggest that the SST pattern effect plays a dominant role for interannual radiative anomalies, and modulates the two-way interaction between SST and radiation in coupled climate variability.

2. Data and Methods

We analyze monthly satellite observations of top-of-atmosphere radiative fluxes obtained from the Clouds and the Earth's Radiant Energy System (CERES) Energy Balanced and Filled (EBAF) Edition 4.1 product (Loeb et al., 2020), over the 20-year period from March 2000 to February 2020. To assess how the radiative anomalies relate to changes in surface temperature and tropospheric stability, we also analyze monthly ERA5 reanalysis data (Hersbach et al., 2019). We use the surface (skin) temperature (hereafter T_{sfc} , equal to the SST over ocean regions) and the estimated inversion strength (EIS; Wood & Bretherton, 2006), a measure of lower-tropospheric stability relevant to low clouds, defined over ocean regions only. We further calculate the Niño-3.4 index (Trenberth, 1997), a measure of the ENSO phase, as the average SST anomaly over the region 190°–240°E, 5°S–5°N.

We obtain the same variables from a set of climate model simulations performed as part of the Coupled Model Intercomparison Project Phase 6 (CMIP6; Eyring et al., 2016). We use two experiments: *amip*, run with prescribed time-evolving SSTs, sea ice and atmospheric composition; and *piControl*, with interactive ocean and sea ice, and constant preindustrial forcing. We include 18 models (Table S1 in Supporting Information S1), with one ensemble member per model. For *amip*, we consider the 20-year period from January 1995 to December 2014, while for *piControl* we use 50 years of data. Note that while the very strong 1997/98 El Niño is only present in the *amip* data, results are consistent across models and observations and the presence of the 1997/98 event does not unduly affect results.

For all variables, we calculate anomalies by subtracting the monthly climatology at every grid point, and remove any linear trend. Prior to analysis, all fields are regridded to a common T42 grid (corresponding to a grid resolution of approximately 2.8° in longitude and latitude), using conservative remapping for radiative fluxes, and bilinear interpolation for other fields. We define tropical means as the area-weighted spatial averages between 30°S and 30°N. To assess out-of-phase relationships between SST, stability and radiation, we use lagged regression analysis, where we calculate the ordinary least squares regression slopes at varying lags between the x and y variables, ranging from -18 to $+18$ months. The resulting lagged regressions can be interpreted as the typical responses to a $+1$ -K anomaly in the Niño-3.4 index (i.e., a moderate El Niño).

3. Relationship Between ENSO and the Radiation Budget

Figures 1a and 1b present the time evolution of anomalies in the Niño-3.4 index, alongside tropical-mean T_{sfc} , EIS, and the net top-of-atmosphere radiative flux N , as quantified from monthly CERES and ERA5 data. T_{sfc} and the Niño-3.4 index vary approximately in tandem and are well correlated ($r = 0.77$; panel a). Meanwhile, EIS and the negative of N also track each other closely ($r = 0.73$, panel b), but follow a somewhat different time evolution compared with the temperature indices in Figure 1a: N only weakly correlates with anomalies in T_{sfc} and Niño-3.4 ($r = -0.20$ and -0.17 , respectively).

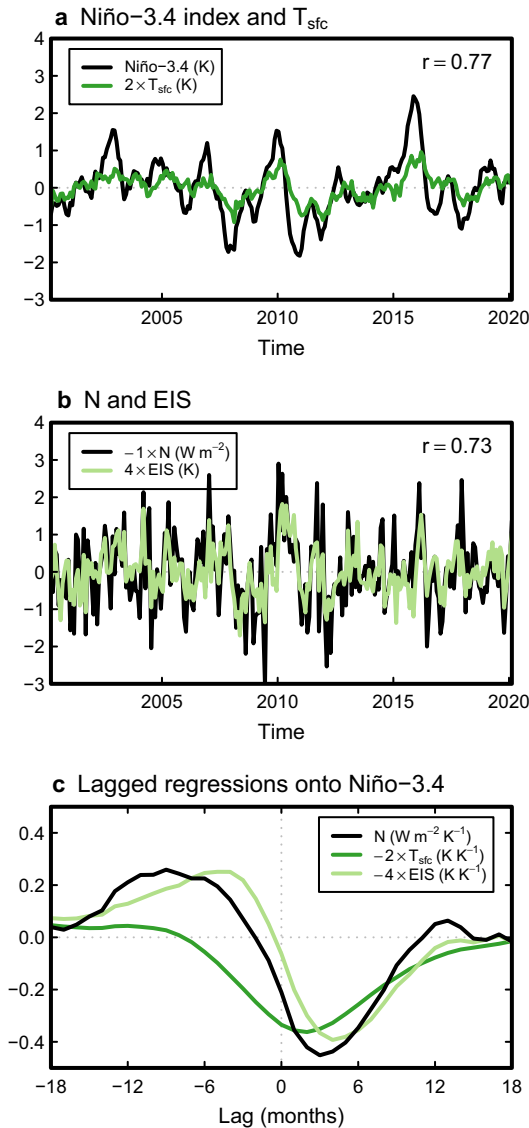


Figure 1. Monthly anomalies in (a) the Niño-3.4 index (black) and tropical-mean (30°S to 30°N) surface temperature T_{sfc} (dark green, arbitrarily rescaled), (b) the negative of the tropical-mean net radiation budget N (black, positive downward) and estimated inversion strength (EIS, light green, arbitrarily rescaled). (c) Lagged regressions of N , T_{sfc} and EIS onto the Niño-3.4 index, showing the least squares regression slopes against lag in months. Positive lags indicate that Niño-3.4 leads. N is calculated from Clouds and the Earth's Radiant Energy System observations, and all other variables from ERA5 reanalysis data.

The strong relationship between area-averaged N and EIS in monthly observations is consistent with previous work (Ceppi & Gregory, 2019). Increased stability (positive EIS) promotes enhanced low-cloud amount and hence anomalous shortwave cloud-radiative cooling (Klein & Hartmann, 1993; Wood & Bretherton, 2006; Zhou et al., 2016); furthermore, an additional smaller cooling effect comes from increased longwave clear-sky emission from the free troposphere (Andrews & Webb, 2018; Ceppi & Gregory, 2017, 2019). Both effects are consistent with the relationship in Figure 1b.

Lagged regression analysis reveals that the anomalies in EIS are approximately 90° out of phase with the Niño-3.4 index (Figure 1c), with the regression slopes peaking around ± 4 months. The evolution of N is also mostly in quadrature with Niño-3.4, but the anomalies peak about 2–4 months earlier than for EIS. By contrast, T_{sfc} anomalies are nearly in phase with Niño-3.4, peaking approximately at +2 months (Trenberth et al., 2002). The N changes associated with a 1-K Niño-3.4 anomaly are of the order of $\pm 0.4 \text{ W m}^{-2}$, and hence of comparable magnitude to the present-day mean imbalance of 0.8 W m^{-2} relative to the pre-industrial era (Loeb et al., 2021). Note, however, that the correlation coefficient between N and Niño-3.4 anomalies peaks at only -0.36 at lag +3 months (not shown), indicating that factors other than ENSO must also contribute to monthly variations in the tropical radiation budget.

The out-of-phase relationship between radiation and temperature in Figure 1c has been noted in prior work (Fueglistaler, 2019; Lutsko, 2018; Lutsko & Takahashi, 2018; Proistosescu et al., 2018; Xie et al., 2016), and it indicates that the radiative anomalies are not simply a response to temperature anomalies following $N = \lambda T_{sfc}$, where $\lambda < 0$ is the climate feedback parameter. The relationship in fact suggests the opposite—that the radiative anomalies force surface temperature during ENSO. In an ocean-atmosphere system in which radiative variability is purely stochastic, that is, unrelated to the SST boundary conditions (Hasselmann, 1976), the one-way forcing of SST by radiation is manifested in a 90° phase shift between radiation and SST anomalies, with radiation leading (see Proistosescu et al., 2018, their Figure 2f), similar to the relationships in Figure 2b. Consequently, the evolution of the radiative budget during the ENSO cycle has been thought to be indicative of stochastic forcing of the ocean by internal atmospheric variability (Xie et al., 2016). However, a different interpretation was proposed by Lutsko and Takahashi (2018), who speculated that the anomalous radiative heating during the ENSO growth phase is in fact driven by cloud responses to SSTs, which then feed back upon ENSO.

The similar time evolution of N and EIS across the observed ENSO cycle (Figure 1c) leads us to refine the hypothesis of Lutsko and Takahashi (2018): rather than reflecting stochastic forcing, the radiative anomalies associated with the ENSO cycle are driven by an SST pattern effect (Gregory & Andrews, 2016; Stevens et al., 2016), mediated by changes in tropospheric stability and their impact on low-cloud amount (Andrews & Webb, 2018; Ceppi & Gregory, 2017, 2019; Zhou et al., 2016). To confirm the role of SSTs, we turn to atmosphere-only *amip* model simulations, and find similar relationships between EIS, N , and the Niño-3.4 index, as compared with observations (Figures 2a and 2b). (The differences between observations and models remain if we restrict the analysis to the common period from March 2000 to December 2014 [Figure S1 in Supporting Information S1], and it is unclear whether they reflect model biases or observational error). Since SSTs are prescribed and hence unresponsive to stochastic,

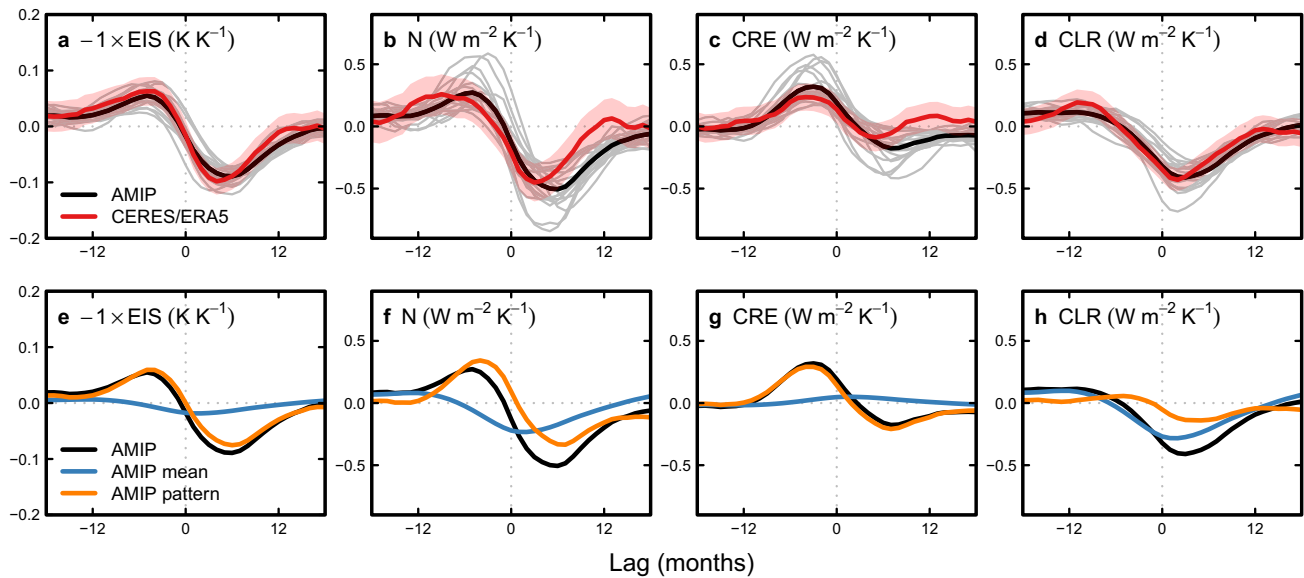


Figure 2. Lagged regressions of tropically averaged variables onto the Niño-3.4 index: (a) the negative of estimated inversion strength (EIS), (b) net top-of-atmosphere radiation budget (N), (c) net cloud-radiative effect (CRE), and (d) net clear-sky radiation (CLR). Red curves denote Clouds and the Earth's Radiant Energy System (CERES) satellite observations and ERA5 reanalysis data, gray curves represent individual *amip* climate model simulations, and black curves denote the *amip* mean. Red shading represents the 95% confidence interval for the regression slopes of the CERES and ERA5 data. Radiative fluxes are defined positive downward. (e–h) As in (a–d) but for the *amip* multimodel mean (black) and the mean sea surface temperature (SST) (blue) and SST pattern (orange) components of the anomalies (see text for details).

internal atmospheric radiative variability in *amip*, the lead-lag relationship between N and Niño-3.4 in Figure 2b cannot be reflective of stochastic forcing; instead, it must result from the imposed SSTs. Importantly, our claim here is not that radiation does not force ENSO, but rather that this forcing is not *stochastic*; instead, it is *predictable* from the SSTs.

The ENSO-related radiative anomalies result from changes in cloud-radiative effect (CRE) and clear-sky radiation which are of comparable magnitude, but exhibit different time evolutions (Figures 2c and 2d). The CRE component, dominated by shortwave changes (Figures S2a and S2b in Supporting Information S1) is responsible for the radiative heating before an El Niño event, while causing modest cooling after the event; meanwhile, the clear-sky component is associated with longwave cooling during and after the ENSO peak (Figures 2d, S2c and S2d in Supporting Information S1), and is more in phase with Niño-3.4. Its time evolution resembles that of $T_{\text{sf}} (Figure 1c)$, suggesting the clear-sky anomalies are dominated by a Planck response to tropical temperature anomalies.

We have verified through composite analysis that similar lagged anomalies of EIS and radiation occur for El Niño and La Niña events taken separately (not shown), suggesting that the relationships in Figures 2a–2d are approximately linear with respect to the Niño-3.4 index. Furthermore, we have verified that the relationships in Figures 2a–2d are not specific to the *amip* period: qualitatively similar lagged relationships are found in the same set of climate models run with interactive SSTs and constant preindustrial forcing (Figure S3 in Supporting Information S1). This indicates that, on average, CMIP6 models are able to simulate the coupling between ENSO and tropical-mean radiation, at least qualitatively. Differences between models and observations in Figure S3 in Supporting Information S1 likely reflect coupled model shortcomings in the details of the ENSO SST patterns and/or in the timing of the ENSO cycle. To understand how the SST patterns associated with ENSO give rise to these radiative changes, we next analyze the geographical patterns of anomalies in tropical SST, EIS, and radiation during the ENSO cycle.

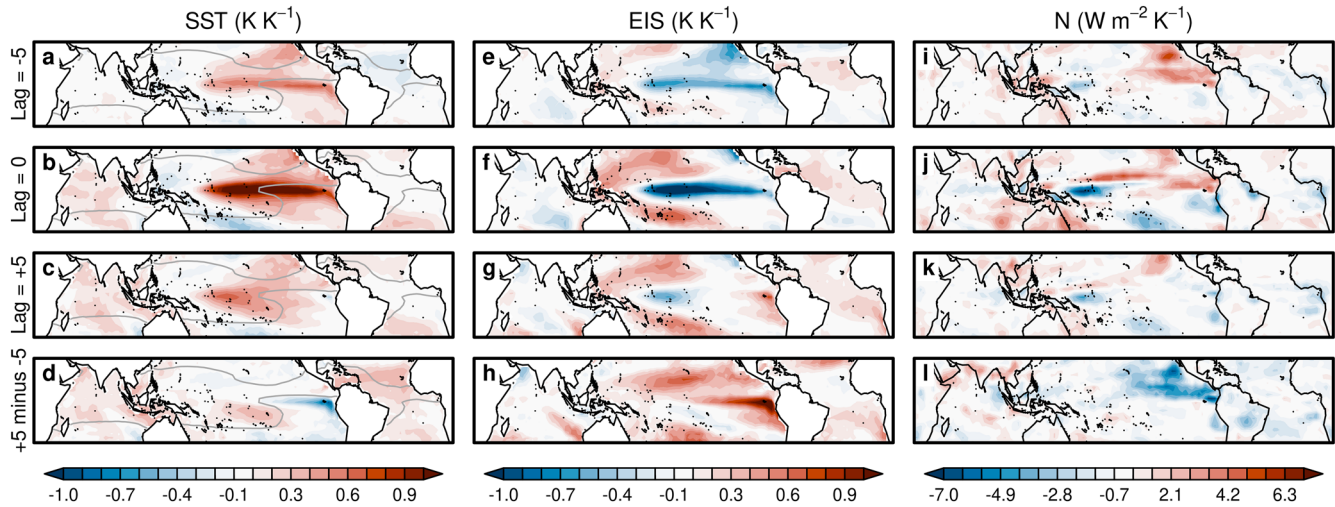


Figure 3. Lagged regression maps of ERA5 sea surface temperature (SST) (a–d) and estimated inversion strength (EIS) (e–h), as well as Clouds and the Earth's Radiant Energy System N (i–l), onto the Niño-3.4 index at lags of -5 , 0 , and $+5$ months from the first to the third row. The fourth row shows the difference between lags $+5$ and -5 . Negative lags indicate that the variables lead the Niño-3.4 index. In panels (a–d), the gray curves indicate the median of the climatological tropical SST distribution (26.8°C).

4. The ENSO Pattern Effect

Figure 3 shows maps of SST, EIS, and N , all regressed onto Niño-3.4 at lags of -5 , 0 , and $+5$ months; lags of ± 5 months are representative of the conditions prevailing at the peak EIS anomalies before and after ENSO (Figure 2a). Although warm SST anomalies cover most of the tropical Pacific during the positive phase of ENSO, they tend to migrate westward over time, toward the warm pool region (Figures 3a–3d; Rasmusson & Carpenter, 1982). Furthermore, SSTs also increase in the Atlantic and Indian Ocean basins between lags -5 and $+5$ months. Together, these changes result in the warm anomalies shifting toward climatologically warm regions during the ENSO cycle (Figure 3d, gray contour). A simpler way to represent this evolution is by binning the data by percentiles of the tropical SST distribution, which clearly shows a migration of the SST anomalies toward high percentiles across the ENSO cycle (Figure 4a; see also Fueglistaler, 2019).

How does the SST pattern evolution result in tropical tropospheric stability anomalies changing sign across the ENSO cycle? A simple theory to relate these variables to one another is based on two assumptions: (a) only the highest-SST regions (relative to the tropical average) are convectively coupled to the free troposphere; (b) the tropical free troposphere cannot sustain large horizontal temperature gradients owing to the

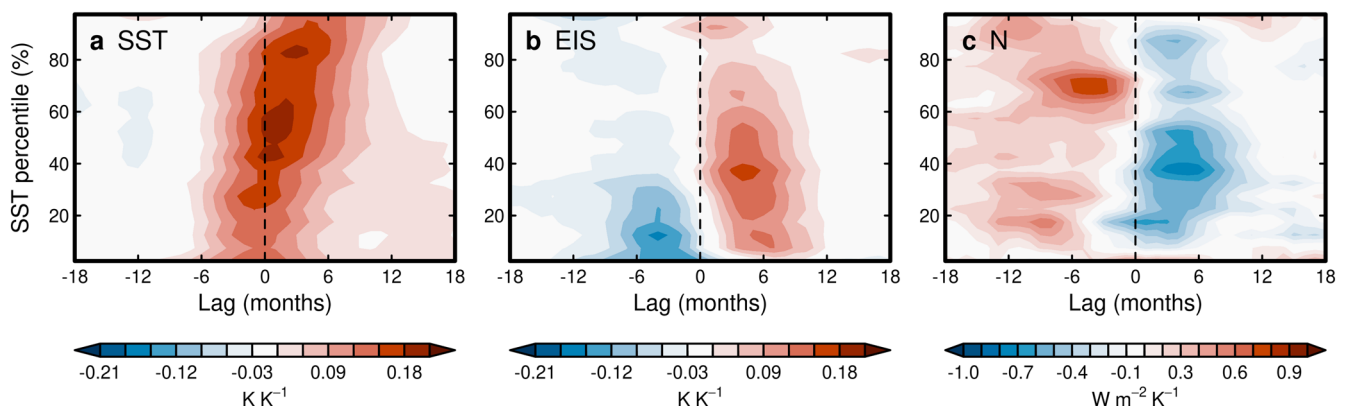


Figure 4. Lagged regressions of tropical (a) sea surface temperature (SST), (b) estimated inversion strength (EIS), and (c) N onto the Niño-3.4 index, binned by percentiles of the monthly varying SST distribution. As in previous figures, the regression slopes represent typical responses to a $+1\text{-K}$ anomaly in the Niño-3.4 index. We use 20 bins in 5% intervals.

small Coriolis parameter, following Weak Temperature Gradient theory (Sobel et al., 2001). Following these assumptions, positive SST anomalies in “warm” regions will warm the entire atmospheric column, and this warming will then rapidly diffuse horizontally, thereby stabilizing the entire tropical troposphere. By contrast, warming in “cool” regions will remain trapped in the boundary layer, thus causing local destabilization with little remote impact (Andrews & Webb, 2018; Ceppi & Gregory, 2017; Zhou et al., 2016). Thus, the pattern of SST changes during the ENSO cycle in Figure 3d is consistent with EIS increasing across the tropics, particularly in climatologically stable regions like the eastern ocean basins (Figures 3h and 4b).

Consistent with the EIS anomalies, the largest ENSO-related radiative changes between lags -5 and $+5$ months occur in the East Pacific (Figure 3l) and are associated with a negative CRE change, dominated by low clouds (Figure S4 in Supporting Information S1). However, weaker negative radiative changes are also observed across much of the tropics, as can be seen in SST percentile space (Figure 4c). Although the low-cloud anomalies bear the signature of EIS changes (compare Figures 3e–3h and S4e–S4h in Supporting Information S1), it should be noted that clouds respond to a variety of other environmental factors including SSTs and the atmospheric circulation (e.g., Myers & Norris, 2013, 2016; Qu et al., 2015), and hence the pattern of radiative changes in Figure 3l is not expected to perfectly match those of SST or EIS anomalies taken individually.

5. Quantifying the SST Pattern Effect

Having demonstrated qualitatively how the character of SST patterns affects tropical stability and radiation during ENSO, we now attempt to quantify this effect. To do so, we decompose the SST anomalies into two components: one associated with tropical-mean changes, and another involving the SST pattern, defined as the deviation of local SST from monthly tropical-mean SST. This follows the approach of Ceppi and Gregory (2019), who found these two components to be additive in experiments with two atmosphere-only climate models.

We first estimate the response to uniform SST changes using the *amip-p4K* and *amip-m4K* experiments, in which SSTs are uniformly increased or decreased by 4 K, respectively. Six of the 18 models provide data for these experiments (Table S1 in Supporting Information S1), and we assume that the multimodel mean response to uniform sea surface warming in this subset is representative of the larger set of models. For the variables of interest, we take the multimodel mean difference between *amip-p4K* and *amip-m4K* and normalize it by the change in tropical-mean SST (i.e., 8 K) to obtain responses per unit tropical warming (Figure S5a in Supporting Information S1). (Taking centered differences between *amip-p4K* and *amip-m4K*, rather than forward differences between *amip-p4K* and *amip*, should give a more accurate estimate of the changes per unit warming where these are not strictly linear with respect to temperature). We then multiply these normalized responses by the ENSO-related tropical-mean SST anomalies at each lag in the *amip* experiments (Figure S5b in Supporting Information S1). The result quantifies the contribution of tropical-mean SST changes to the lagged anomalies in stability and radiation during the ENSO cycle (Figures 2e–2h, blue curves).

We then estimate the response to the ENSO SST pattern as the difference between the total *amip* anomalies and the mean SST component (Figures 2e–2h, orange curves). Note that the result is virtually identical if we calculate the total *amip* response using only the six models with ± 4 K experiments (not shown). As expected, mean SST changes explain most of the clear-sky radiative anomalies, consistent with a Planck response (Figure 2h), although we also find a small pattern contribution, consistent with the dependence of longwave emission on the tropospheric lapse rate (Andrews & Webb, 2018; Ceppi & Gregory, 2017). Furthermore, the pattern effect accounts for nearly all of the ENSO-related CRE changes (Figure 2g), reflecting the strong dependence of low-cloud amount on tropospheric stability (Figures S4e–S4h in Supporting Information S1; Klein & Hartmann, 1993; Wood & Bretherton, 2006). Overall, the SST pattern explains the majority of the ENSO-related anomalies in N (Figure 2f), closely tracking the pattern-induced EIS anomalies (panel e).

Integrated over the entire ENSO event (crudely defined here as extending from lags -12 to $+12$ months), the tropical radiative response to ENSO warming is negative in the *amip* mean, with -1.7 ZJ (10^{21} J) net energy loss through the top of the atmosphere. We calculate that this is almost entirely due to the mean SST component (-1.6 ZJ), with the cumulative SST pattern contributions nearly canceling out due to the sign

change around lag zero. Thus, even though the pattern component dominates the instantaneous radiative anomalies at most lags (Figure 2f), the integrated radiative budget change is determined mainly by the damping Planck response to mean SST changes. The SST pattern effect acts to delay this radiative damping by several months, relative to what would be expected from a simple Planck response.

6. Summary and Conclusions

Variability in the top-of-atmosphere tropical radiation budget is approximately 90° out of phase with ENSO events, with anomalous radiative heating before an El Niño, and anomalous cooling thereafter (and vice versa for La Niña). Prior work proposed that this lagged relationship between radiation and ENSO is a manifestation of stochastic forcing of the ocean by internal atmospheric variability. By contrast, here we demonstrate that these ENSO-related radiative anomalies are in fact primarily due to an SST pattern effect, mediated by changes in tropospheric stability.

During the ENSO growth phase, SST anomalies develop mainly in climatologically cool regions (e.g., the East Pacific), but migrate toward warm regions as the event peaks (Fueglistaler, 2019). Because SST anomalies in cool versus warm regions have opposite impacts on tropical-mean stability, the SST evolution causes stability anomalies to change sign across the ENSO cycle. This in turn explains the opposite-signed radiative anomalies during the ENSO growth and decay phases, which are consistent with stability-induced low-cloud amount changes. Changes in tropical-mean SST do also contribute to the radiative changes, mainly through changes in clear-sky longwave cooling.

Our findings are suggestive of a possible two-way coupling between the radiation budget and natural variability: since changes in N are not a simple Planck response, they may also feed back onto ENSO itself. However, the nature of this feedback remains unclear, with conflicting results in past literature. In an analysis of climate model simulations with and without cloud feedback, Middlemas et al. (2019) find that shortwave cloud anomalies lead to ENSO events decreasing in both amplitude and persistence; by contrast, using a different model, Rädel et al. (2016) conclude that longwave cloud anomalies amplify ENSO variability. Although the lead-lag relationships in this study suggest that cloud-radiative anomalies “force” ENSO, a regional analysis would be necessary to confirm this and demonstrate the possible causal links between local radiative anomalies and SST tendencies.

The dominant role of stability for short-term unforced radiative anomalies (Figure 1b) suggests that the ability of climate models to represent natural variability may depend on their simulation of the low-cloud sensitivity to tropospheric stability (Yuan et al., 2018). Previous work has demonstrated very large model spread in this regard, with some models even simulating the wrong sign of the relationship between EIS and low-cloud amount in tropical stratocumulus regions (Qu et al., 2015). Furthermore, CMIP models from phases 5 and 6 also underestimate the sensitivity of stratocumulus clouds to local SST (Myers et al., 2021). These biases could result in incorrect cloud-radiative feedbacks on coupled modes of variability, leading to errors in the timing or amplitude of these modes. Future research should assess the implications of cloud biases for coupled climate variability, and particularly for the known discrepancies between models and observations in Pacific SST variability over recent decades (Fueglistaler & Silvers, 2021).

Data Availability Statement

All data sets used in this study are publicly available. CERES EBAF Ed4.1 data were obtained from <https://ceres.larc.nasa.gov/data/>. ERA5 data were downloaded from <https://doi.org/10.24381/cds.f17050d7>. CMIP6 model output was obtained from <https://esgf-node.llnl.gov/search/cmip6/>.

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