New Indices for Better Understanding ENSO by Incorporating Convection Sensitivity to Sea Surface Temperature

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ABSTRACT

Observed outgoing longwave radiation (OLR) data indicate that convection is nonlinearly sensitive to sea surface temperature anomalies (SSTA) for background SSTs in the 25.25°–30.25°C high-impact range. In this study, we use that observed convection sensitivity to derive a proxy of the convective responses to SSTA only [referred to as *fluctuations of the accumulated convection strength* (FACT)]. FACT reproduces the pattern of the observed convection response to ENSO in the central and eastern Pacific, but underestimates the amplitude due to the exclusion of the effect of ENSO-induced atmospheric convergence anomalies on convection. We thus use FACT to define new indices (InFACT) of ENSO diversity that explicitly account for the nonlinear convection–SST sensitivity. The amplitude of InFACT allows us to easily classify El Niño events into weak, moderate, and strong types that markedly differ in terms of SSTA spatial patterns and their convective responses. La Niña events classified by InFACT display much less pattern diversity, and mostly differ through their amplitudes. Finally, our study supports some previous studies that the nonlinear SST–convection relation plays a strong role for the development of extreme El Niño events with the presence of high-impact SSTs and large convection anomalies in the equatorial eastern Pacific.

1. Introduction

El Niño–Southern Oscillation (ENSO) is the most energetic air–sea coupled mode at the interannual time scale, and has been intensively studied as the major source of global climate variability (Clarke 2008). When sea surface temperature (SST) warms up (El Niño) or cools down (La Niña), the intensity and location of the atmospheric deep convection change as well. But as shown in Fig. 1, the largest changes of convection are shifted west by about 40° relative to the maximal ENSO

SST anomalies (SSTA). Moreover, the strongest convection anomalies occurs 1–2 months after the SSTA maxima, indicating an influence of the background SST seasonal cycle (Stuecker et al. 2013). A key reason for the spatial and temporal shift of convective response is that deep atmospheric convection depends on a SST threshold near 27°C (e.g., Gadgil et al. 1984; Graham and Barnett 1987). Because of this dependence, the traditional SSTA-based ENSO indices provides limited information on the convective response, except in the equatorial central Pacific (e.g., Lau et al. 1997).

The convection–SST relationship is in fact more complicated than a simple SST threshold for deep convection (Graham and Barnett 1987; Waliser and Graham 1993; Zhang 1993; Bhat et al. 1996; Lau et al. 1997). When SST is below the threshold, deep convection is rarely observed and convection is insensitive to SST changes, but shallow convection does occur. Around the threshold, a relatively small change of SST will induce a rapid change in convection, indicating a large convection–SST sensitivity.

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FIG. 1. Hovmöller diagrams of the monthly mean sea surface temperature (SST; shading) and outgoing longwave radiation (OLR; brown contours for positive values and green contours for negative values) anomalies during the life cycle (from January of the developing year 0 to October of the decaying year 1) in the (a) eastern Pacific (EP) El Niño composite, (b) central Pacific (CP) El Niño composite, and (c) La Niña composite. The superimposed white thick contours are the 27°C SST isotherm, the vertical black dashed lines indicate the zonal coverage of the Niño-4 and Niño-3 regions, and the black solid lines present the peak month (November) of ENSO composites. Each variable is averaged between 5°S and 5°N. See the [appendix](#) for the identification method and individual event in the ENSO composite.

But over higher SSTs, the convection–SST sensitivity is weak again (e.g., [Waliser and Graham 1993](#)), although deep convection does occur and sometimes intensifies with increasing SST. As argued by [Lau et al. \(1997\)](#), the convection–SST sensitivity over such high SST strongly depends on the presence or absence of large-scale wind convergence: convection decreases with increasing SST under divergent conditions, while it continues to increase with SST in regions of convergent winds.

Accounting for the deep convection SST threshold is important to understand ENSO and its pattern and amplitude diversity as well. There are two types of El Niño events ([Larkin and Harrison 2005](#); [Ashok et al. 2007](#); [Kao and Yu 2009](#); [Kug et al. 2009](#); [Capotondi et al. 2015](#); [Timmermann et al. 2018](#)), one with the SSTA maxima in the eastern Pacific (EP type; [Fig. 1a](#)) and the other with largest SSTA in the central Pacific (CP type; [Fig. 1b](#)). (See the [appendix](#) for the method to classify El Niño events as EP or CP type.) For EP El Niño events,

the SSTA is large enough to allow SST to cross the 27°C threshold and therefore to induce remarkable changes of convection across the equatorial Pacific (Fig. 1a). But for CP El Niño events, SSTA is weak in the eastern Pacific and therefore SST remains below 27°C, with little increase in the eastern Pacific convection as a result (Fig. 1b). The deep convection SST threshold is believed to play a strong role in the differentiation of the EP and CP El Niño events (Takahashi and Dewitte 2016; Takahashi et al. 2019). The development of atmospheric deep convection in the eastern Pacific acts as a switch for strong local Bjerknes feedback to induce strong EP El Niño.

Therefore, it is not surprising that Chiodi and Harrison (2010, 2013, 2015) could identify strong and weak El Niño events according to an equatorial central to eastern Pacific convection index, without considering differences in the SSTA spatial patterns. The identified strong El Niño events have a large convective response and are accompanied with large SSTA and SST over 27°C in the eastern Pacific: most strong El Niño events are thus EP type. On the other hand, weak El Niño events display SSTA and convection anomalies confined to the central Pacific, and are therefore of the CP type. It hence indicates a relation between the intensity and pattern of El Niño events (Takahashi et al. 2011; Dommenget et al. 2013; Capotondi et al. 2015). However, unlike El Niño, La Niña events display weak pattern diversity but variable SSTA and convection amplitudes (Kug et al. 2009; Kug and Ham 2011; Chen et al. 2015), and the reason remains less understood.

The convection response thus seems to be a good way to characterize ENSO diversity. But as mentioned above, convection response is jointly influenced by changes in SST and the atmospheric wind convergence. The former influence can be understood as a local effect by considering SST-dependent changes in the local evaporation (Zebiak 1986), and the latter one is a nonlocal effect depending on the low-level moisture convergence driven by SST and its anomalies, known as the convergence feedback (Zebiak 1986; Webster 1981). Before defining a convection index, it is necessary to establish more intuitive proxies of the SST-dependent convection alone. Okumura (2019) made a good attempt by connecting convection response to the SST deviations from the deep convection threshold rather than from the climatology, that is, $\Delta T = (T - T^*)H(T - T^*)$, where T^* is the deep convection threshold and H is the Heaviside function. The newly defined SST deviations explain the spatial distribution of convection anomalies quite well. Similarly, Williams and Patricola (2018) used the unweighted average of longitudes of SST above the deep convection threshold, and argued that this averaged longitude is more useful than SSTA center to describe the ENSO SSTA pattern diversity. However, these approaches assumed that the sensitivity of convection to SST follows a

Heaviside function that neglects the effect of SSTA that allows a SST transition from below to above deep convection threshold. In the current study, we develop a method to estimate the changes of convection induced by SSTA alone that explicitly accounts for the observed nonlinear convection–SST sensitivity rather than a Heaviside function–like sensitivity. Another goal of this study is to design new ENSO indices that track the spatiotemporally variable convection anomalies induced by ENSO SSTA alone.

The rest of this paper is structured as follows. Data and methodology are introduced in section 2. Section 3 introduces the convection–SST sensitivity and how it can be incorporated to estimate the SSTA-dependent convection changes. Section 4 describes the general features of the SSTA-dependent ENSO convection anomalies. Section 5 introduces new ENSO indices that consider the nonlinear convection–SST sensitivity and the resultant ENSO classification. Section 6 gives a summary.

2. Data and method

The observational data used in this study are the monthly NOAA Optimum Interpolation SST (Reynolds et al. 2002), the NOAA interpolated outgoing longwave radiation (OLR; Liebmann and Smith 1996), and the low-level wind convergence obtained from the vertically averaged winds between 850 and 1000 hPa from NCEP–DOE Reanalysis II (Kanamitsu et al. 2002) during the 1982–2016 period. Here, OLR is used as a proxy for atmospheric convection. In addition, winds from ECMWF ERA5 (Copernicus Climate Change Service 2017) are also adopted to test the result sensitivity on data source. All data are detrended and filtered using a 3-month running mean filter, and are then averaged into a coarser spatial resolution of $2.5^\circ \times 2.5^\circ$ (latitude–longitude) in the 20°S – 20°N , 120°E – 80°W domain to focus on the large-scale variations only. Besides, results based on data from the entire tropical ocean are compared with those from the tropical Pacific only.

Because SST, convection, and low-level wind circulation are complexly related to each other, the relationships of SST, OLR, and low-level wind convergence are established by sorting one variable as a function of another, following the approach of Graham and Barnett (1987). In each 0.25°C SST bin, OLR and wind convergence are sorted, and the corresponding mean values, standard deviations, and numbers of grid points are calculated. Similarly, mean OLR value and the standard deviation from the mean are calculated in each 10^{-6} s^{-1} wind convergence bin. Through this, the relationship between any two variables excludes the influence from the other one, to some extent.

FIG. 2. Relationships of SST, OLR, and low-level wind convergence in the tropical Pacific (20°S–20°N, 120°E–80°W) during 1982–2016. Scatterplots of (a) OLR and (b) 850-hPa wind convergence in each 0.25°C SST bin, and (c) OLR in each 10^{-6} s^{-1} wind convergence bin. In each panel, the red curve and vertical bar are the mean and ± 1 standard deviation with respect to mean in each bin, and the black curve is the corresponding numbers of grids. (d) The sensitivity of OLR to SST as defined in Eq. (1). (e), (f) As in (d), but for the sensitivity of wind convergence to SST and sensitivity of OLR to wind convergence, respectively.

3. Nonlinear SST–convection relationship

As shown in Fig. 2a, the intensity and occurrence frequency of the tropical Pacific convection (OLR) fluctuate in a broad range in each SST bin, especially when SST is high. These fluctuations indicate the influence from other factors to convection, such as from the low-level wind convergence (Zebiak 1986; Graham and Barnett 1987; Zhang 1993; Lau et al. 1997; Back and Bretherton 2009). By averaging OLR in each SST bin, such influences can be removed, and the mean OLR (OLR*; red curve in Fig. 2a) can be roughly considered as the part of OLR that depends on SST alone. Because the interaction between SST and convection is two-way, as revealed by He et al. (2018), one potential factor that cannot be removed is the one-way influence from convection to SST, especially when SST is high. It should be noted here that the SST–convection relationship differs in different Pacific regions (e.g., Lau et al. 1997; Sabin et al. 2013; see Fig. S1 in the online supplemental material), the mean SST–convection relationship shown by the red curve in Fig. 2a is therefore a global relationship for

the tropical Pacific that neglects such local differences. As a reminder here, the relationships of OLR, SST and wind convergence in the following text are referred to as such global relationships, unless particularly indicated.

The SST–convection relationship indicates that the SST-induced convection intensifies monotonically as SST warms up from about 25.25° to 30.25°C. The SST–wind convergence relationship shows that the low-level wind convergence generally enhances as SST increases, and the low-level winds start to converge when SST exceeds 27°C (Fig. 2b). Similar dependence of wind convergence on SST is also found in the ERA5 wind data (Fig. S2). Furthermore, the strengthening of the low-level wind convergence leads to a monotonic intensification of convection (Fig. 2c). Although SST, wind convergence, and convection are mutually coupled, the mean values shown by the red curves in Figs. 2a–c indicate a simplified description of their complex relationships: positive SSTA in the 25.25°–30.25°C range can enhance convection and low-level wind convergence, which reinforce convection, in particular when SST is above 27°C.

FIG. 3. Comparisons of (a),(c) relationships between SST and convection (indicated by OLR) and (b),(d) convection sensitivity to SST in the tropical Pacific (red lines) and the entire tropical oceans (purple lines) quantified from (top) monthly and (bottom) climatological data. The gray dots in (a) and (c) denote the individual convection value in each SST bin in the tropical Pacific.

a. Convection sensitivity to SST

The convection sensitivity to SST (convection–SST sensitivity) at each SST bin can be expressed as follows:

$$\frac{\partial \text{OLR}^*}{\partial T} = \frac{\text{OLR}^*(T + \Delta T) - \text{OLR}^*(T - \Delta T)}{2\Delta T}, \quad (1)$$

where ΔT is the SST bin (0.25°C). The convection–SST sensitivity displays a strong nonlinearity: once SST exceeds 25.25°C, the sensitivity increases with SST until SST reaches 28.75°C, and the sensitivity decreases until SST reaches 30.25°C (Fig. 2d). It indicates that the 25.25°C SST acts as a switch for convection in the tropical Pacific. This convection threshold also holds in the

tropical Atlantic and Indian Oceans (Johnson and Xie 2010; see also Fig. 3b and Fig. S3b). Moreover, the strongest convection–SST sensitivity occurs around a SST of 28.75°C and is 3 times as large as that at the 27°C convective SST threshold.

The turndown of the convection–SST sensitivity at SST beyond 28.75°C indicates that other factors start to show greater but negative impacts on convection. One possible candidate is the local air subsidence associated with nearby deep convection (Lau et al. 1997). SST around the core of the warm pool is not as high as that in the core, but the horizontal SST gradient and the associated wind convergence is strong enough to induce local convection and generate remote subsidence and

wind divergence to weaken the wind convergence over the core of the warm pool (Lau et al. 1997; Sabin et al. 2013). Under such circumstance, convection enhances at a decreasing rate over such high SST. Beyond the SST range of 25.25°–30.25°C, the convection–SST sensitivity is weak, unsteady, and reversed. Interestingly, there are some unique features at 27°C SST: the low-level winds on average start to converge (Fig. 2b), and the wind convergence exhibits the highest sensitivity to SST (Fig. 2e), which further leads to the highest convection sensitivity to wind convergence (Fig. 2f). These features provide a statistical explanation of regarding 27°C as the SST threshold for deep convection.

The convection–SST sensitivity obtained here is in agreement with some previous conclusions (e.g., Lau et al. 1997) and is not very sensitive to different spatial domains (Figs. 3a,b). However, it is slightly different from the precipitation–SST sensitivity obtained by He et al. (2018), who used climatological SST to force an atmospheric model and found that the precipitation sensitivity to SST in the entire tropical oceans increases monotonically with SST at an even larger rate at high SST beyond 28°C (see similar results in Figs. 3c,d). We notice that our result is quite consistent with that of He et al. and only differs at high SST over 29.5°C. In a climatological view, SST, convection, and wind convergence are well correlated to each other (Fig. S4). But when sorted from the monthly data, the diversity of individual convection in any SST bin is much larger than that sorted from the climatological data (cf. Figs. 3a and 3c). Moreover, the climatological winds converge over high SST beyond 28°C (Fig. S4b), which makes convection sensitive to SST (Lau et al. 1997).

Note that the number of convection samples decreases sharply when SST exceeds ~28.75°C (Fig. 3a), and it is extremely small for SST around 30°C (on the order of 10^3), so it is well possible that the SST threshold identified at 30.25°C from the monthly data results from the impact of small-scale convection on SST. For instance, during a dry phase of Madden–Julian oscillation (MJO) in the tropical western Pacific, convective clouds are suppressed so that the solar radiation can heat the sea surface and produce such high SST (Woolnough et al. 2000; Waliser et al. 2004; DeMott et al. 2016). Therefore, the convection–SST sensitivity quantified from monthly data is more suitable for investigating ENSO because it covers a broader range of SST. But honestly, the convection–SST relationship from the climatological data will not result in significant differences in estimating the changes of convection during ENSO, because ENSO SSTA rarely occurs in a background SST near 29°C or yields to absolute SST over 30.25°C.

b. Efficiency of SST and accumulated convective strength

As seen in Figs. 2d and 4a, the thresholds of 25.25° and 30.25°C bracket the SSTs that have high potential to generate convection. Hence, they are the so-called high-impact SSTs. The convection–SST sensitivity in this range is defined as the *efficiency of sea surface temperature* (EOT) in generating convection [Eq. (2)]:

$$\text{EOT}(T) = \begin{cases} \frac{\partial \text{OLR}^*}{\partial T}, & 25.25^\circ \leq T \leq 30.25^\circ\text{C} \\ 0, & \text{otherwise} \end{cases} \quad (2)$$

Beyond the high-impact SST range, EOT is set to zero (Fig. 4a). This zero-EOT setting is reasonable because convection changes little for a 2°C SST increases from 24° to 26°C, and it is much less than the changes in OLR^* ($\sim 29 \text{ W m}^{-2}$) induced by a 2°C SST increase from 27° to 29°C (Fig. 4b). In the high-impact SST range, EOT can be expressed as quasi-linear functions of SST as follows:

$$\text{EOT}(T) \cong \begin{cases} -6.07T + 155.65, & 25.25^\circ \leq T \leq 29.0^\circ\text{C} \\ 17.62T - 530.93, & 29.0^\circ\text{C} < T \leq 30.25^\circ\text{C} \end{cases} \quad (3)$$

The coefficients of determination R^2 in the two functions are 0.96 and 0.93, respectively.

Because of the dependence of EOT on SST, it is needed to integrate EOT with respect to SST to estimate the OLR that depends on the high-impact SST [e.g., Eq. (4)], through which the simultaneous changes in SST and EOT are considered. The integration is defined here as the *accumulated convective strength* (ACT), which differs from OLR^* only when SST is beyond the high-impact SST range.

$$\text{ACT}(T) = \int_{T_0}^T \text{EOT}(T) dT + \text{OLR}^*(25.25^\circ\text{C}). \quad (4)$$

Here, T_0 is set to 20°C, but it does not change the ACT as long as its value is smaller than 25.25°C. Following the definition, ACT is actually the size of the area below the curve of EOT (Fig. 4b). In this form, ACT accounts for the OLR that depends on SST only, not the part of OLR induced by wind convergence.

4. Fluctuation in ACT: A proxy of SSTA-induced change in convection

a. Definition of FACT

Again, due to the nonlinear dependence of EOT on SST, the fluctuation of ACT (FACT) induced by SSTA

FIG. 4. (a) A schema of the efficiency of SST (EOT) in generating convection, accumulated convective strength (ACT), and the fluctuation in ACT (FACT). (b) Two examples are shown to indicate the changes of ACT induced by a 2°C change of SST from 24°C to 26°C (light green lines) and from 27°C to 29°C (orange lines) that corresponds to the orange shading in (a). The gray shading in (a) presents the changes of ACT associated with changes of SST from 27°C to 29°C if assuming a constant EOT at 27°C.

cannot be estimated from the first-order Taylor expansion [$\text{EOT}(T) \times \Delta T$]. Instead, FACT should be estimated as

$$\begin{aligned} \text{FACT}(T, \Delta T) &= \text{ACT}(T + \Delta T) - \text{ACT}(T) \\ &= \int_{T_0}^{T+\Delta T} \text{EOT}(T) dT - \int_{T_0}^T \text{EOT}(T) dT \\ &= \int_T^{T+\Delta T} \text{EOT}(T) dT \end{aligned} \quad (5)$$

In this form, FACT is the size of the area under EOT between T and $T + \Delta T$ (Fig. 4a) and is a proxy of changes in OLR induced by SSTA only. Only when T or $T + \Delta T$ falls into the high-impact SST range does FACT get a nonzero value. For instance, for a 2°C SSTA from 24°C to 26°C, the high-impact SSTA value is only 0.75°C (from 25.25°C to 26°C) and the resulting FACT is about 1.7 W m⁻², while the high-impact SSTA value is 2°C when SST changes from 27°C to 29°C and the corresponding FACT is about 29 W m⁻² (Fig. 4b). The different values of the high-impact SSTAs and their resulting convection changes in the basis of different background SST indicate that it is necessary to incorporate the nonlinear convection–SST sensitivity to understand ENSO and its convection response.

b. General features of FACT during ENSO

When ENSO occurs, the associated FACT that is induced by the high-impact SSTA can be expressed in the following form:

$$\text{FACT} = \int_{T_m}^T \text{EOT}(T) dT, \quad (6)$$

where T is the monthly total SST and T_m is the corresponding climatological monthly mean SST. In a similar manner, SSTA can be expressed in the following form that assumes a constant 100% EOT for all SST:

$$\text{SSTA} = \int_{T_m}^T 100\% dT. \quad (7)$$

Because of the seasonally varying SST and EOT, FACT contains the influence from the seasonality of SST, implying a nonlinear interaction between ENSO and seasonal cycle (e.g., Stuecker et al. 2013). Our idea about FACT is similar to that of Okumura (2019), but we use a continuous and nonlinear convection–SST sensitivity quantified from observations rather than a Heaviside function–like sensitivity with a cutoff SST around 27°C. Our approach consider the convection response to the SSTA that allows SST to vary between 25.25°C and 27°C.

As shown in Fig. 5, the evolution of the equatorial FACT is similar to that of OLR anomalies (OLRA) to surprising detail but with underestimated amplitude due to the exclusion of the convergence feedback. Although ENSO SSTA almost occupies the entire equatorial central-to-eastern Pacific (Fig. 5a), notable FACT and OLRA are confined in the equatorial central Pacific, where SST exceeds 25.25°C (Figs. 5b,c). Furthermore, the largest FACT and OLRA locate to the west of 27°C

FIG. 5. Hovmöller diagrams of monthly (a) SSTA, (b) FACT, and (c) OLRA along the equator (averaged between 5°S and 5°N) during 1982–2016. The contour intervals for SSTA and FACT (OLRA) are 2°C and 16 W m⁻², respectively. The vertical green lines indicate the Niño-4 and Niño-3 regions, and the thick solid and thin dashed purple contours indicate the 27° and 25.25°C SST isotherms, respectively.

SST where relatively weak local SSTA generates the largest convection response because of high background SST and large EOT. But over relatively cooler cold tongue region where SST is below 25.25°C, little FACT or OLRA is detected even though local SSTA is sometimes sizable, which clearly indicates the dependence of convection anomalies on background SST. In addition, the strongest OLRA locates to the west of the largest FACT by about 10°, indicative of the role of moisture advection by the easterly trade winds (Sherwood 1996; Sherwood et al. 2010) that is neglected when estimating FACT.

Figure 6 displays a clearer spatial similarity between FACT and OLRA by dividing ENSO events into EP El Niño, CP El Niño, and general La Niña types (see the appendix for the classification method). During strong EP El Niño events, like the 1982/83, 1997/98, and 2015/16 events, the basinwide SSTs rapidly warm up above 25.25°C and thus make most SSTAs become high-impact SSTAs, and remarkable negative FACT and OLRA subsequently spread eastward into EP (Figs. 6a,d). But during the moderate CP El Niño (i.e., 1994/95 and 2002/03) and all La Niña events, FACT and OLRA are confined in the central Pacific and rarely extend into EP, because EP SST is still below the convection “switch-on” threshold (Figs. 6b,c,e,f). In addition, FACT and OLRA both reach their maximum in January of ENSO decaying year, which lags the peak phase of ENSO SSTA by about two months, indicative of the effect of seasonal cycle on convection as defined in Eq. (6). Overall, the similar temporal evolutions and spatial distributions between FACT and OLRA validate our method of estimating the anomalous convection induced by ENSO SSTA alone.

Along the equatorial Pacific, OLRA and SSTA are negatively correlated with higher correlation in the eastern Pacific and lower in the western Pacific (blue dashed line in Fig. 7a). As a proxy for the ENSO SSTA-induced OLRA, FACT shows an increased negative correlation with SSTA (blue solid line in Fig. 7a), in particular in the western and central Pacific. Because FACT excludes the contribution from wind convergence to convection (see Fig. 5c), it is not surprising that OLRA and FACT in the western and central Pacific are not correlated as highly as they do in the eastern Pacific (Fig. 7a), and the standard deviation of FACT is only 30%–50% as large as that of OLRA (Fig. 7b). Nevertheless, FACT is able to present the largest convection variability in the central Pacific, as a typical convection response to the largest SST variation in the eastern Pacific. Attributed to the close connection between FACT and SSTA (Fig. 7a), FACT is positively skewed in the western Pacific, corresponding to the negatively skewed SSTA, and it exhibits increasing negative skewness toward the equatorial eastern Pacific (blue solid line in Fig. 7c), following the

increasing positive skewness of SSTA (red solid line in Fig. 7c). In contrast, the skewness of OLRA starts to decrease eastward from 140°E (blue dashed line in Fig. 7c).

5. Indices of FACT (InFACT) and the resultant ENSO classifications

Following Eqs. (8) and (9), new ENSO indices of FACT (InFACT) are defined by separately averaging the positive and negative FACT values over the entire equatorial Pacific (5°S–5°N, 120°E–80°W). This approach follows the idea of Karnauskas (2013) in designing the Niño-Infinity and Niña-Infinity indices for the warm and cold ENSO phases. The advantage of such definition is that it implies no priori focus on any specific region and can account for opposite signals at different longitudes.

$$\text{InFACT}^+(t) = \overline{\text{FACT}^-(t)}, \quad (8)$$

$$\text{InFACT}^-(t) = \overline{\text{FACT}^+(t)}. \quad (9)$$

Here, the overbars indicate the area average in the abovementioned domain, and the superscript plus and minus signs denote the positive and negative phases. For instance, El Niño induces negative FACT values in the central to eastern Pacific (Fig. 5b), so the warm ENSO index InFACT^+ is calculated by collecting the negative FACT values (FACT^-).

Figure 8a shows the InFACT^+ and InFACT^- time series, along with red and blue dots as identifiers of peak phases of qualified ENSO events according to NOAA’s definition that is based on the Niño-3.4 index (see the detailed definition in the appendix). All NOAA-identified ENSO events (Fig. 8c and shown as dots in Figs. 8a,b) exhibit InFACT values beyond plus and minus one standard deviation ($\pm 1\sigma$) (Fig. 8a). The standard deviation of InFACT^+ ($\sigma^+ = 4.75 \text{ W m}^{-2}$) is almost twice that of InFACT^- ($\sigma^- = 2.41 \text{ W m}^{-2}$), revealing a strongly negatively skewed distribution ($\sigma^+/\sigma^- = 1.97$) in FACT and a greater asymmetry than SSTA, as previously shown in Fig. 7c. This amplitude asymmetry is related to the location of high SST beyond 27°C. As shown in Fig. 8b, such high SSTs extend more eastward than its climatological place during El Niño events, in particular the strong ones, while they retreat more westward during La Niña events. As a result, positive SSTAs in the equatorial central-to-eastern Pacific are more efficient than negative SSTAs to change FACT, thus producing larger amplitude in InFACT^+ .

Based on the normalized InFACT^+ and InFACT^- (by their standard deviations) values, we propose a new ENSO classification criteria based on whether the January–March (JFM) mean InFACT values fall into the ranges of $1-2\sigma$,

FIG. 6. Comparison of (a)–(c) FACT with (d)–(f) OLRA along the equator (averaged between 5°S and 5°N) during the traditionally identified (left) EP Niño, (center) CP El Niño, and (right) all La Niña events using the Niño-3.4 method. Shading presents the associated SSTA, and contours denote FACT in (a)–(c) and OLRA in (d)–(f). The white thick and thin contours indicate the 27° and 25.25°C SST, respectively. See the [appendix](#) for the ENSO classification method.

$2-3\sigma$, and $>3\sigma$ for at least 5 consecutive months. As a result, ENSO events are divided into weak, moderate, and strong types. The reason for the choice of JFM mean rather than the traditional December–February (DJF) mean is that FACT is influenced by the seasonal cycle and reaches its maxima 1–2 months later than SSTA, as shown in [Fig. 6](#).

The identified events are shown in [Table 1](#). In this study, the 1992/93 weak El Niño event is a qualified El Niño according to InFACT^+ , while it is not identified by the Niño-3.4 index. Most positive SSTAs of this event are in the left half of the Niño-4 region ([Fig. 5b](#)) so that the Niño-3.4 SSTA index misses it. But the background SSTs are above

FIG. 7. Statistical features of SSTA, FACT, and OLRA along the equator (averaged between 5°S and 5°N). (a) Correlation coefficients between each two variables, (b) standard deviations, and (c) skewness. Colors of the y axis and lines correspond to each other.

27°C, which leads to notable FACT and InFACT⁺ values that are large enough to meet the criteria for weak El Niño.

The spatial patterns of JFM FACT and DJF SSTA of the three ENSO types identified from InFACT are displayed in Fig. 9. Strong El Niño events display maximal SSTA in the Niño-3 region, with the largest FACT in the Niño-3.4 region (Fig. 9a). The entire equatorial Pacific is occupied by high SST over 27°C. This group is so distinct that it can easily be identified using other ENSO classification methods (e.g., Chen et al. 2015; Takahashi et al. 2011). Moderate El Niño events exhibit SSTA maxima straddling the Niño-3 and Niño-4 regions, with maximal FACT in the Niño-4 region (Fig. 9b). Meanwhile, high SST beyond 27°C only occupies the west half of the Niño-3 region. For weak El Niño events, the largest SSTA and FACT are both located in the Niño-4 region, and the 27°C SST resides near the Niño-4 region (Fig. 9c). It seems that our El Niño classification is compatible with El Niño's intensity-location dependence as noticed by Okumura (2019). Strong El Niño events are of the EP type, while moderate El Niño events are of a marginal EP El Niño type or a mixed El Niño type that shows comparable Niño-3 and Niño-4 SSTA indices values (Lee and McPhaden 2010; McPhaden et al. 2011), except for the strongest CP El Niño event in 2009/10. All the weak events identified here are of the CP type. Across the three El Niño types, FACT and SSTA gradually decreases from the equatorial central to eastern Pacific, and the 27°C SST gradually retreats westward, suggestive of a decrease in the nonlinearity

of the Bjerknes feedback. This ENSO classification confirms the previous conclusion again that the presence of 27°C SST in EP is very likely the essential mechanism that gives rise to strong EP El Niño (Takahashi and Dewitte 2016; Takahashi et al. 2019). This critical SST is required to collapse the mean wind divergence (Fig. 2b), and allow deep convection to develop in the eastern Pacific so that local Bjerknes feedback can be significantly enhanced to support the growth of local SSTA.

Unlike the three types of El Niño events that display distinctive patterns depending on their intensity, the identified three La Niña types share similar patterns but differ in their intensities. SSTA maxima are located in the Niño-3.4 region, with the largest FACT in the Niño-4 region where local SSTs are still higher than 27°C (Figs. 9d–f). This makes the subdivision of La Niña into several types ambiguous, as already pointed out by some previous studies (Kug et al. 2009; Kug and Ham 2011; Chen et al. 2015). Large positive FACT values, meaning suppressed convection, also extend from the equatorial central Pacific into the Southern Hemisphere, following the seasonal distribution of the warm pool in late boreal winter. Because of the absence of high SST in the equatorial eastern Pacific, the strong and moderate La Niña types almost mirror the moderate El Niño type in the SSTA and FACT patterns, while the weak La Niña type is more like a mirror of weak El Niño type. Because FACT is a proxy of the anomalous convection generated by the high-impact SSTA alone, the strong ENSO events identified here are nearly the same as the OLR-ENSO

FIG. 8. (a) Indices of FACT (InFACT) for the positive (red) and negative (blue) ENSO phases during 1982–2016. The light, medium, and dark shading denote 1, 2, and 3 times the standard deviation, and the red (blue) dots are the peak months of the El Niño (La Niña) identified by the Niño-3.4 SSTA index in (c). The size of each dot corresponds to ENSO intensity indicated by the ratio of InFACT value and its standard deviation. (b) East edge of warm pool identified by longitude of 27°C SST (black line) and its climatological monthly mean (light red shading) along the equator (averaged between 5°S and 5°N). (c) Monthly Niño-3.4 SSTA index. The El Niño and La Niña episodes with Niño-3.4 SSTA exceeding $\pm 0.5^{\circ}\text{C}$ are filled with red and blue colors, respectively.

events (the events with clear OLRA) identified by [Chiodi and Harrison \(2010, 2013, 2015\)](#), while some moderate and all weak ENSO events correspond to the non-OLR ENSO events (the events without clear OLRA).

6. Summary

Many studies have revealed that convection, SST, and wind convergence are complexly coupled to each other ([Graham and Barnett 1987](#); [Waliser and Graham 1993](#); [Zhang 1993](#); [Lau et al. 1997](#)). In this study, the coupled relationships of convection, SST, and low-level wind convergence were examined using up-to-date data, and it was found that convection initiates at a SST threshold

of about 25.25°C and monotonically increases with the SST above this threshold. The convection sensitivity to SST (convection–SST sensitivity) is useful in identifying the high-impact SSTs in the range of 25.25°C – 30.25°C , in which the SST variability leads to significant convection changes. This sensitivity increases with SST between 25.25° and 28.75°C and decreases up to 30.25°C . The existence of the so-called SST threshold for deep convection at 27°C is well possibly due to the initiation of low-level wind convergence at this SST that significantly enhances convection. The nonlinear convection–SST sensitivity and the existence of convection threshold explain the occurrence of the largest ENSO-induced convection anomalies to the west of the 27°C SST rather

TABLE 1. Individual events of each ENSO type identified by InFACT. The year in boldface indicates an event qualified in InFACT but not in the Niño-3.4 SSTA index.

ENSO types	Criteria (the range for InFACT values)	Individual event	
		El Niño	La Niña
Strong	$>3\sigma$	1982/83, 1997/98, 2015/16	1988/89, 1998/99, 1999/2000, 2007/08, 2010/11
Moderate	$2-3\sigma$	1986/87, 1991/92, 2009/10	1983/84, 1984/85, 2011/12
Weak	$1-2\sigma$	1987/88, 1992/93 , 1994/95, 2002/03, 2004/05, 2006/07	1995/96, 2000/01, 2005/06, 2008/09

than over the strongest SSTA (Fig. 1). This nonlinear convection–SST sensitivity has been taken into account when studying ENSO pattern diversity (Takahashi and Dewitte 2016; Okumura 2019). Most SSTA-based ENSO indices do not consider such a nonlinearity, and therefore provide limited intuitive information on the convection response.

By integrating the nonlinear convection–SST sensitivity, we developed a simple yet reasonable method to estimate the convection anomaly that depends on the local effect of SSTA but neglects the nonlocal effect of anomalous wind convergence. The estimated SSTA-dependent convection anomaly is defined as the *fluctuation of accumulated convection strength* (FACT), which provides a proxy of total convection anomaly as a function of SSTA and background SST climatology. Because of the increasing convection–SST sensitivity in the 25.25°–28.75°C SST range, over which ENSO often occurs, positive SSTAs induce larger FACT values than negative ones, and induce progressively larger FACT values over warmer SST backgrounds. It implies that the developments of El Niño increases the Bjerknes feedback whereas La Niña decreases it.

Compared to SSTA, FACT is a better proxy in characterizing ENSO owing to its closer relations with both SSTA and convection response. We designed a pair of indexes based on FACT (InFACT⁺ and InFACT[−] for the warm and cold ENSO phases) by separately averaging the basinwide negative and positive FACT signals. InFACT⁺ allows to sort out El Niño events in various spatial pattern groups based on the peak-phase index values. On the other hand, La Niña events identified by InFACT[−] have very little diversity in their spatial patterns and just differ in their intensities. The different intensity-pattern interdependence between El Niño and La Niña is caused by different extensions of the high-impact SST of 27°C and warmer background SST. It indicates that incorporating the nonlinear convection–SST sensitivity into define ENSO SSTA can provide a new way to characterize ENSO and its diversity in a convection perspective.

Our results support the conclusions of Takahashi and Dewitte (2016) and Takahashi et al. (2019) that the presence of 27°C SST in the equatorial eastern Pacific is crucial to the emergence of strong EP El Niño events. First, 27°C SST is needed to collapse the local mean wind divergence in the equatorial eastern Pacific and initiate additional convection associated with wind convergence (Fig. 2b). Second, when SST warms up above 27°C, positive SSTA will induce increasingly larger convection anomalies, partly because of the simultaneous increase in EOT and partly due to the presence of wind convergence. It results in a sudden and significant increase in the local Bjerknes feedback, which largely enhances the EP SSTA growth rate. But for CP El Niño events, EP SST is under 27°C (Fig. 7b) and local winds are still divergent (e.g., Xiang et al. 2013), and the local Bjerknes feedback and SSTA growth rate are consequently weaker than those in the EP El Niño events. Such differences mean that it is the different increase of the nonlinearity of the EP Bjerknes feedback, caused by the dependence of wind convergence on the 27°C SST threshold, that eventually leads to the different amplitude of EP SSTA between the EP and CP El Niño events. In the opposite manner, negative SSTA would induce increasingly less convection anomalies and thus decrease the nonlinearity in the EP Bjerknes feedback, so less pattern diversity is found among La Niña events.

Furthermore, the positive asymmetry of ENSO amplitude can be inferred from the nonlinear convection–SST sensitivity. As Geng et al. (2019) argued, the nonlinearity and asymmetry in the convection response to SSTA dominate the genesis of the positive ENSO amplitude asymmetry in the eastern Pacific. Even assuming the same initial positive and negative SSTA in the central to eastern Pacific, the positive SSTA can induce larger convection and wind responses, which further causes larger thermocline response to wind and, in turn, greater SST response to thermocline variability. Through this asymmetric response chain, positive SSTA grows faster, and the final amplitude of El Niño is larger.

FIG. 9. Identified (top) strong, (middle) moderate, and (bottom) weak ENSO types in their mature phases: (a)–(c) El Niño and (d)–(f) La Niña. Shading and black contours are for January–March mean FACT and December–February mean SSTA, respectively. The red dashed boxes indicate the Niño-4 and Niño-3 regions, and the purple thick and thin contours indicate the 27° and 25.25°C SST isotherms. See Table 1 for the members of each type.

Despite the advantages of our method, several limitations still remain. First, EOT is a global estimation of the convection sensitivity to tropical Pacific SST that neglects local differences as shown in Fig. S1. So EOT underestimates the importance of SST for convection somewhere in the tropical Pacific but overestimates it elsewhere. Local EOT may be more helpful in examining regional climate response to SSTA. Second, EOT removes the influence from wind convergence to convection, and the resultant FACT maxima induced by ENSO are at the east of strongest OLRA (Figs. 5 and 7).

Nevertheless, EOT can be used as an observational basis to assess the relative importance of SST for convection in complex climate models, as done by He et al. (2018). The difference between observational and modeled EOT may provide a possible way to evaluate the simulation biases in the tropical Pacific mean state and ENSO. Similar convection–SST sensitivity, although not carefully constrained, has been adopted by some intermediate complexity coupled models for a better estimation of the atmospheric heating release related with SSTA (Wang and Li 1993; Xie et al. 2015). The simulated atmospheric heating can be further improved by transforming FACT to SSTA-induced heating component and by integrating the convection–wind convergence sensitivity (Fig. 2f) to obtain the convergence-induced component. In addition, because the SST threshold for convection shows an upward trend of about $0.1^{\circ}\text{C decade}^{-1}$ since 1980 (Johnson and Xie 2010), it is required to update EOT every 2–3 decades to obtain an optimal knowledge of the SST–convection relationship in the tropical Pacific.

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APPENDIX

ENSO Classification Using the Niño-3.4 Method

ENSO is usually quantified by several SSTA-based indices in the equatorial central to eastern Pacific, such as the

Niño-4 index (SSTA averaged in 5°N – 5°S , 160°E – 150°W), Niño-3.4 index (SSTA averaged in 5°N – 5°S , 170° – 120°W), and Niño-3 index (SSTA averaged in 5°N – 5°S , 150° – 90°W). According to NOAA's definition, an El Niño (La Niña) event is identified when the 3-month running-mean Niño-3.4 index exceeds $+0.5^{\circ}\text{C}$ (-0.5°C) for a minimum of five consecutive overlapping seasons.

El Niño events are often divided into two types according to their different spatial distributions of the strongest sea surface temperature anomalies (SSTA). An El Niño event is identified as an eastern Pacific (EP) El Niño event if the mature phase [December–February (DJF)] Niño-3 index is greater than the Niño-4 index; otherwise, it is classified as a central Pacific (CP) El Niño event (Kug et al. 2009; Yeh et al. 2009). Based on this classification method, there are 6 EP El Niño events and 5 CP El Niño events, where the former are the 1982/83, 1986/87, 1991/92, 1996/97, 2006/07, and 2015/16 events and the latter the 1987/88, 1994/95, 2002/03, 2004/05, and 2009/10 events. When a general El Niño composite is carried out, all events are averaged.

The same criteria can be used for La Niña classification; the EP La Niña type includes the 1984/85, 1995/96, and 2005/06 events, and the CP La Niña type contains the 1983/84, 1988/89, 1998/99, 1999/2000, 2000/01, 2007/08, 2008/09, 2010/11, and 2011/12 events. However, the spatial patterns of two La Niña types are not as distinct as the those of two El Niño types (Kug et al. 2009; Kug and Ham 2011; Chen et al. 2015), and most La Niña events are like CP type. Therefore, if not specified, we consider all La Niña events as one type.

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