Two new sea surface temperature anomalies indices for capturing the eastern and central equatorial Pacific type El Niño-Southern Oscillation events during boreal summer

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Using monthly mean data from the Hadley Center and the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis, we have constructed two new indices \( I_{CP} \) and \( I_{EP} \) of boreal summer sea surface temperature anomalies (SSTA) in equatorial Pacific for period of 1963–2016 by employing methods including the six-order polynomial fitting and pattern correlations. The new indices \( I_{CP} \) and \( I_{EP} \) are almost independent of each other. Using these two indices, we are able to successfully capture the main features of central Pacific (CP) and eastern Pacific (EP) type SSTA variations in tropical Pacific in both spatial and temporal. The EP-type SSTA events vary on inter-annual timescales whereas CP-type events vary on both inter-annual and inter-decadal. For the CP-type events, stronger positive (negative) SST anomalies are observed in central tropical Pacific while weaker SSTA in the Maritime Continent (MC) and eastern equatorial Pacific during positive (negative) phase of index \( I_{CP} \). However, for EP-type events, the stronger SSTAs appear in both the equatorial Pacific region east of dateline and Peruvian coastal ocean while weaker SSTAs in MC and western equatorial Pacific regions. Both the anomalous heating induced by CP- and EP-type SSTA may force the atmosphere to respond, resulting in different types of anomalous patterns of circulations, rainfall, and near-surface air temperatures. These results indicate that the new indexes are useful for our better investigating the CP- and EP-type summer SSTA events as well as their climate impacts, thereby providing a clue to monitoring and predicting strong SSTA events in equatorial Pacific.

KEYWORDS
boreal summer, climate variation, El Niño/La Niña, sea surface temperature anomaly pattern, SSTA index

1 | INTRODUCTION

The El Niño-Southern Oscillation (ENSO) is well known as the strongest inter-annual signal in our climate system. It has profound impacts on the climate conditions all over the globe. Usually, the El Niño events occur in the eastern equatorial Pacific. However, as reported in some early studies, it also occurs as a different type of phenomenon with the centre of the large positive sea surface temperature anomalies (SSTA) in the central equatorial Pacific (Rasmusson and Carpenter, 1982; Fu et al., 1986; Wang, 1995). Since the late of the 20th century, this kind of the El Niño events is called as the Central Pacific (CP) type El Niño.
Various SSTA indexes as mentioned above have been defined and successfully employed in describing CP- and EP-type SSTA events. However, there are still some questions that need to be considered. First, there are several pairs of SSTA indices defined by performing the EOF analysis (Ashok et al., 2007; Kao and Yu, 2009; Takahashi et al., 2011). This is a little complicated and is sometime not easily to be used. For instance, supposing a new ENSO event occurred, the leading EOF patterns of SSTA may be changed to some extent if we do or do not take this new event into account during performing EOF analysis. Therefore, it is necessary to define the indices in a new way in which the indices are more easily to be calculated. Second, if we do the joint regression–EOF analysis as in Kao and Yu (2009), there is still some weak correlation between EP and CP indexes, which is not perfect as we expect. Thus, we have to define these two indices that must be statistically independent of each other, or at least, the correlation must be as smaller as possible. Third, the SSTA patterns are usually season-dependent due to the ENSO cycles. That means that the SSTA pattern in boreal summer may be different from that in winter. In this case, the leading EOF patterns of SSTA are also different in different seasons.

Based on the above analysis, we think it is necessary to seek for a new way of defining the indexes of EP- and CP-type SSTA for different seasons. These newly defined SSTA indices should be calculated in an easier way and independent of number of samples of SSTA events. As is known, the most striking difference between signatures of EP and CP types of ENSO is the zonal distribution of SSTA. Based on this spatial pattern difference, it is possible for us to develop a new set of SSTA indices for EP and CP types of SSTA events. In this study, we investigate this possibility and provide two new SSTA indexes to characterize the CP- and EP-type SST anomalies in the equatorial Pacific during the Northern Hemisphere summer.

2 | DATA AND METHODOLOGY

2.1 | Data

The following data are used: (a) global monthly average SSTs with horizontal resolution of $1 \times 1^\circ$ from the Hadley Center during the period of 1963–2016 (Rayner et al., 2003); (b) National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis including winds and temperatures with a resolution of $2.5 \times 2.5^\circ$ in horizontal and 12 isobaric levels from 1,000 to 100 hPa in vertical for period of 1963–2016 (Kalnay et al., 1996); (c) monthly rainfall from the NOAA CPC Merged Analysis of Precipitation (CMAP) spanning the period of 1979–2016 (Xie and Arkin, 1997); and (d) Oceanic Niño Index (ONI) data (Smith et al., 2008; Huang et al., 2015) for period of 1963–2016 available at

Niño events have been occurring more and more frequently with different climate impacts as compared to those induced by the canonical El Niño events (Yeh et al., 2009; Lee and McPhaden, 2010). This evokes scientists to investigate the different types of El Niño events as well as their different climate impacts. Ashok et al. (2007) examined a kind of anomalous oceanic events with warm SSTAs centred in the equatorial central Pacific (CP) and coined the name as “El Niño Modoki.” Other scholars have referred to these events as the “dateline El Niño” (Larkin and Harrison, 2005), “warm pool El Niño” (Kug et al., 2009), and “central Pacific type El Niño” (Kao and Yu, 2009). On the other hand, the El Niño events with a positive SST anomaly centred in the eastern equatorial Pacific along the coast of Peru are referred to as “canonical-type El Niño,” “cold tongue El Niño,” and “eastern Pacific El Niño.” For convenience, in this paper, we use the terms “eastern Pacific type” (EP type) and “central Pacific type” (CP type) to describe these two types of ENSO events.

Several sets of SSTA indices have been proposed by different research groups for our better investigating the EP-type and CP-type ENSO and their effects on climate variations (Sullivan et al., 2016). Earlier indexes were primarily based on the spatial distribution of the SSTA in the equatorial Pacific during an El Niño event. For example, based on the anti-phase relationship of SST anomalies between the CP and both the EP and western Pacific, Ashok et al. (2007) defined the EMI index (El Niño Modoki index) to identify CP-type El Niño events. Kug et al. (2009) examined the central and eastern types of ENSO based on the intensifications of SST anomalies in region Niño3 and region Niño4. In the same year, Kao and Yu (2009) developed a joint regression–EOF (empirical orthogonal function) method, with which the KaoCP and KaoEP indices are defined to depict these two types of El Niño events, but KaoCP is still correlated with KaoEP though the coefficient is not so large. Similarly, Yu and Kim (2013) calculated pattern correlations between original SSTA and residual EP/CP type SSTA over $10^\circ$S–$10^\circ$N to obtain their pattern index. To capture signals of the EP-type and CP-type ENSOs better, Takahashi et al. (2011) performed a 45° orthogonal rotation of the two leading EOF modes of the SSTA in the equatorial Pacific and derived an approximate orthogonal rotation of the two leading EOF modes of the SSTA. Based on this spatial pattern difference, it is possible to define these two indices that must be statistically independent of each other, or at least, the correlation must be as smaller as possible. Third, the SSTA patterns are usually season-dependent due to the ENSO cycles. That means that the SSTA pattern in boreal summer may be different from that in winter. In this case, the leading EOF patterns of SSTA are also different in different seasons.

Based on the above analysis, we think it is necessary to seek for a new way of defining the indexes of EP- and CP-type SSTA for different seasons. These newly defined SSTA indices should be calculated in an easier way and independent of number of samples of SSTA events. As is known, the most striking difference between signatures of EP and CP types of ENSO is the zonal distribution of SSTA. Based on this spatial pattern difference, it is possible for us to develop a new set of SSTA indices for EP and CP types of SSTA events. In this study, we investigate this possibility and provide two new SSTA indexes to characterize the CP- and EP-type SST anomalies in the equatorial Pacific during the Northern Hemisphere summer.
http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml. In this paper, the summer average means the average over June–July–August (JJA). JJA mean climatology of a quantity is defined as the multi-year averages of the JJA mean of this quantity over period 1963–2012 except for rainfall and air temperature over period of 1979–2012.

2.2 Methods

Beside some statistical methods including regression analysis, wavelet analysis, and EOF analysis, we also use the sixth-order polynomial fitting to mimic the spatial distribution of the SSTA, which is expressed as

\[ F_{\text{type}-X}(\lambda) = \sum_{n=0}^{6} a_n\mu^n(\lambda - \lambda_0)^n, \]

where \( \lambda \) is the longitude in arc and \( \lambda \in D_p : [\lambda_0, \lambda_E] \) holds. The tropical Pacific zonal domain \( D_p : [\lambda_0, \lambda_E] \) starts from \( \lambda_0 \) that is the reference longitude with \( \mu\lambda_0 = 120^\circ \) (or \( \mu\lambda_0 = 120^\circ\text{E} \)) and ends at \( \lambda_E \) with \( \mu\lambda_E = 280^\circ \) (or \( = 80^\circ\text{W} \)). The symbols \( \mu \) and \( a_n \) are arc-degree conversion constant (\( \mu = 180^\circ/\pi \)) and fitting coefficients, respectively. Subscription type-\( X \) of function \( F_{\text{type}-X}(\lambda) \) represents the CP or EP type of SST anomaly events.

The indices including Niño3, Niño3.4, Niño4, and Niño1+2 are employed in this paper, which are, respectively, the regional averages of SSTA over Niño3 (150°–90°W, 5°S–5°N), Niño3.4 (170°–120°W, 5°S–5°N), Niño4 (160°E–150°W, 5°S–5°N), and Niño1+2 (90°–80°W, 0°–10°S). The ONI is defined as 3-month running mean of the Niño3.4 (Smith et al., 2008; Huang et al., 2015). The EMI index of Ashok et al. (2007) is also used, which is defined as EMI = [SSTA]_A \( - 0.5[SSTA]_B \= 0.5[SSTA]_C \), where the subscripts \( A, B, \) and \( C \) represent the areal averaged SSTA over regions (165°E–140°W, 10°S–10°N), (125°–145°E, 10°S–20°N), and (110°–70°W, 15°S–5°N), respectively. The KaoCP and KaoEP indexes are calculated using the joint regression–EOF method as presented by Kao and Yu (2009). In Kao and Yu (2009), they do the EOF analysis using the annual averages of SSTA but we use the summer average in the present paper.

The United States National Oceanic and Atmospheric Administration (NOAA) defines an El Niño (La Niña) event as one in which the value of the ONI index is equal to or greater than 0.5 °C (less than \(-0.5^\circ\text{C}\)) continuously for 5 months. Based on this definition, first, the El Niño and La Niña years are identified. Second, in these identified ENSO years, we designate SSTA events with absolute value of ONI larger than 0.5 °C in any of the three summer months (JJA) as summertime El Niño or La Niña events. Furthermore, we designate the time periods when the absolute value of the ONI index in summer increases, remains almost constant, and declines as the strengthening, matured, and weakening stages of the summer ENSO events, respectively.

3 TWO NEW SSTA INDICES

Based on the difference in zonal distributions between CP- and EP-type SSTA in summer, we reconstruct two indices of SSTA, respectively, referring as CP-type SSTA index (I_{CP}) and EP-type SSTA index (I_{EP}).

3.1 Polynomial functions for spatial pattern of CP- and EP-type SSTA

The CP-type ENSO/El Niño Modoki events have been discussed a lot (e.g., Ashok et al., 2007; Kao and Yu, 2009; Kug et al., 2009; Feng et al., 2010; Takahashi et al., 2011). This kind of El Niño events have a signature of the largest SSTA appearing in equatorial CP. To develop the CP-type SSTA index in summer, some years when summer CP-type SSTA events occur are roughly selected (Feng et al., 2010) based on what are reported in the literatures by different research groups (e.g., Donguy and Dessier, 1983; McPhaden, 2004; Ashok et al., 2007) and year-by-year screenings of the summer SSTA. The criteria for roughly selecting those CP-type years are (a) the significant and large positive SST anomalies in region (170°E–130°W) of the central equatorial Pacific; (b) the negative or weak positive SSTA anomalies in the eastern and western equatorial Pacific; and (c) temperature gradients pointing in opposite directions from the CP to the east and west.

Similarly, for the positive EP-type SSTA events, the criteria are (a) the significant and large positive SSTA in region (120°–85°W) of the tropical EP; (b) the negative or weak positive anomaly in both the equatorial central and western Pacific; and (c) the almost single-signed gradient of SSTA between the eastern and the rest part of equatorial Pacific.

Similar criteria are set for the negative SSTA events in summer. Because time of atmospheric response to the SSTA forcing is about 1 month, when we select the years, the persistence of SSTA with EP- or CP-type signature should be at least 1 month. Based on these above criteria, we have roughly identified the CP- and EP-type SSTA years as listed in Table 1.

To get the spatial pattern of CP- and EP-type SSTA, the SSTAs in tropical Pacific are first averaged in meridional over region (5°S–5°N), which can be denoted as \( T_{55} \) for convenience. Then, composite analyses are performed of SSTAs for CP- and EP-type years of the SSTA events in boreal summer, and the polynomial fittings according to Equation 1 are hence forth conducted of the composite zonal patterns of the CP and EP type of SSTAs (Figure 1). It is seen from Figure 1a,b that the SSTA patterns of both positive and negative SSTA events are characterized by the
TABLE 1 Years when CP- and EP-type SSTA events occur in the tropical Pacific, which are only used for constructing the spatial pattern functions. Years listed here are some out of the 54 study years

| SSTA types | Positive SSTA years | Negative SSTA years |
|------------|---------------------|---------------------|
| CP type    | 1977, 1992, 1994, 2004 | 1974, 1975, 1999, 2011 |
| EP type    | 1972, 1976, 1983, 1997 | 1970, 1973, 1988 |

largest anomalies around region (180°–140°W). These look typically the CP-type SSTA patterns that satisfy the criteria as set above. From Figure 1d,e, the typical EP-type SSTA patterns are observed with the largest anomalies over region (100°–90°W), satisfying the criteria for EP-type events.

The six-order polynomial fitted curves for different SSTA patterns mimic well the distributions of SSTA for different type of SSTA events. Let $F_{CP}(\lambda)$ and $F_{EP}(\lambda)$ be, respectively, the six-order polynomial fitted curve in $F_{1c,f}$, which is the function of $\lambda$. Then the coefficients $a_n$ for $F_{CP}(\lambda)$ are listed in line for SSTA$_{CP}$ in Table 2 and those coefficients for $F_{EP}(\lambda)$ are in line of SSTA$_{EP}$ in the same table. The $F_{CP}(\lambda)$ and $F_{EP}(\lambda)$ will be considered as the spatial pattern for constructing the indexes of CP- and EP-type SSTA anomalies.

Interestingly, it is found that pattern correlation between CP and EP patterns, that is, $r(F_{CP}(\lambda), F_{EP}(\lambda))$ is found to be $-0.07$, which is very small, indicating that the function of CP-type SSTA is almost orthogonal in space to that of EP-type SSTA. Note that the pattern correlation at equator between KaoCP SSTA and KaoEP SSTA during summer is 0.2 which is bigger than $r(F_{CP}(\lambda), F_{EP}(\lambda))$, implying possible contaminations when the KaoCP and KaoEP indices are obtained. Therefore, the functions $F_{CP}(\lambda)$ and $F_{EP}(\lambda)$ could be used to better distinguish the CP- from EP-type of SSTA events. Based on the functions $F_{CP}(\lambda)$ and $F_{EP}(\lambda)$, two new SSTA indices can be easily constructed for CP and EP type of SSTA events in tropical Pacific during boreal summer.

3.2 | CP- and EP-type SSTA indexes

To examine how the summer SSTA in each different year is similar to $F_{CP}(\lambda)$ and/or $F_{EP}(\lambda)$ in spatial, we calculate the pattern correlations of summer SSTA with $F_{CP}(\lambda)$, and with $F_{EP}(\lambda)$, respectively, for all the 54 study years. These pattern correlations denoted by $r_{CP}(t)$ and $r_{EP}(t)$ (see Appendix) are displayed in Figure 2a,b, respectively. Because there are 240 grid points at equator, the spatial distribution of SSTA will look much similar to the spatial pattern $F_{CP}(\lambda)$ or $F_{EP}(\lambda)$ when the absolute of pattern correlation coefficient is larger than 0.55. As seen in Figure 2a, there are many strong CP-type SSTA years though the intensity of SSTA is stronger or weaker. Similar situations can also been seen in Figure 2b for EP-type SSTA years.

To better characterize and distinguish the spatial patterns of these SSTA events, we artificially choose region A (179°–145°W, 5°S–5°N) and region B (112°–84°W, 5°S–5°N) as two key regions, named, respectively, as Central Box (CB) and Eastern Box (EB), for us to get the large enough values of areal mean SSTA anomalies for constructing the CP-type and EP-type SSTA indices. Here, zonal domains of region A and region B are, respectively, defined as the place with the value of the fitted curve of the CP-type SSTA (Figure 1c) not less than 1.2, and the place with the value of fitted curve of the EP-type SSTA (Figure 1f) not less than 3.0. Hence, the absolute magnitude of the regional mean SSTA during summer in these key regions are used to characterize the intensity of the CP- and EP-type SSTA and are combined with the coefficient of spatial similarity of the SSTA ($r_{CP}$ and $r_{EP}$) to yield the new indexes of the CP- and EP-type SSTA anomalies, that is, the $I_{CP}$ and $I_{EP}$, respectively. Thus, these two indexes are finally to be expressed as

$$I_{CP} = |[SSTA]_{CB}| \cdot r_{CP}(t),$$

$$I_{EP} = |[SSTA]_{EB}| \cdot r_{EP}(t),$$

where the $[SSTA]_{CB}$ and $[SSTA]_{EB}$ are the SSTA averaged over region A and region B, respectively. The normalized time series of $I_{CP}$ and $I_{EP}$ are displayed in Figure 2c,d.

There are totally nine (seven) strong positive (negative) CP-type SSTA events ($I_{CP} \geq 1.0$) (Figure 2c) and seven (eight) strong positive (negative) EP-type ones ($I_{EP} \geq 1.0$) (Figure 2d) in boreal summer during period of 1963–2016. Out of these 31 strong SSTA events, 23 events occur in ENSO years, especially in the developing phase (denoted by Es or Ls) of the ENSO events. This suggests, on the one hand, that most of ENSO events persist to boreal summer. On the other hand, there still occur nine strong summer SSTA events with no coincidence with ENSO. This is very interesting. People may pay very little attention to these nine events but the simultaneous influences of these events on summer climate in many regions may be very large.

Note that there occur 10 CP-type events after 1990 while there are only 4 strong EP-type events during the same period, indicating the CP-type events tend to occur far more frequently than the EP-type events do. This interesting phenomenon is in agreement with the findings of Yeh et al. (2009). In addition, it is found that both CP- and EP-type events with relatively stronger SSTA may co-occur simultaneously in 1987 and 2015 (Figure 2c,d). Particularly, $I_{CP}$ and $I_{EP}$ exceed one standard deviation in these 2 years. This event may be referred to as a mixed type one that deserves further examinations. The asymmetry coefficients (Wei, 2007) of ICP and IEP have been calculated, which are $-57.4$ and $5.7$, respectively, indicating that the stronger CP-type SSTA events tend to be La Niña type whereas the
Strong EP-type events tend to be El Niño type in boreal summer.

The summertime CP and EP types of SSTA vary with different periodicities. Based on a wavelet analysis of indexes $I_{CP}$ and $I_{EP}$, it is found that the CP-type events occur with a primary period of 2–7 and 8–14 years (Figure 3) while the EP-type events do with a period of 2–6 years. It is consistent with previous studies that have

![Figure 1](image)

**FIGURE 1** Composites of SSTAs in years of CP- and EP-type SSTA events in boreal summer. The SSTAs are pre-processed by having them averaged over region (5°S–5°N) in tropical Pacific. The dashed lines are for the composite SSTAs whereas the solid lines for the six-order polynomial fitted curves. Composite SSTAs for positive (negative) years of CP-type SSTA are shown in (a, b) whereas shown in (c) are the composited difference of CP-type SSTAs between positive and negative years. Shown in (d, e, f) are, respectively, same as (a, b, c) but for EP-type SSTA events.

**TABLE 2** Fitting coefficients of CP and EP type of SSTA patterns. Patterns $SST_{ACP}$ and $SST_{AEP}$ are corresponding to (c, f), respectively

| Patterns | $a_0$  | $a_2$  | $a_3$  | $a_5$  | $a_4$  | $a_6$  | $a_8$  |
|----------|--------|--------|--------|--------|--------|--------|--------|
| $SST_{ACP}$ | 6.32e-2 | −3.51e-2 | 8.62e-4 | 2.26e-5 | −5.74e-7 | 3.95e-9 | −8.74e-12 |
| $SST_{AEP}$ | −5.74e-1 | 3.43e-2 | −3.24e-3 | 1.11e-4 | −1.53e-6 | 9.42e-9 | −2.16e-11 |
shown decadal signal is stronger in the CP then that in the east (Luo and Yamagata, 2001; Sullivan et al., 2016). This difference suggests that it is indeed necessary to investigate the two types of summertime SSTA events separately.

3.3 Comparison of two new indexes with other existing SSTA indices

The ability of the new indexes $I_{CP}$ and $I_{EP}$ can be partly examined by analyzing the simultaneous correlations of them with other various SSTA indexes. In Table 3 we provide these correlations. It is found in Table 3 that the correlation between $I_{CP}$ and the $C$ index of Takahashi et al. (2011) is the best, followed by the correlations with the SST anomaly index in region Niño4 and with the CP-type El Niño index KaoCP (Kao and Yu, 2009). Index $I_{EP}$ is almost perfectly correlated with indexes Niño1+2, Niño3, and the $E$ index proposed by Takahashi et al. (2011); the correlation coefficients are larger than 0.9. The correlation between $I_{EP}$ and the EP-type index KaoEP of Kao and Yu (2009) is also very high with coefficient value of 0.86. All these correlations indicate that our summer SSTA indexes $I_{CP}$ and $I_{EP}$ are consistent with the existing SSTA indexes, showing the good reliability in describing the two classes of SSTA events. Note that the correlations of Niño3.4 with $I_{CP}$ and $I_{EP}$ are nearly equal, that is, 0.69 and 0.77, respectively. This equal coefficients indicate that total variance of Niño3.4 index can be explained with almost one half by $I_{CP}$ and another half by $I_{EP}$, suggesting that the Niño3.4 is just a right index for capturing both the CP and EP type of SSTA events. That is to say, the Niño3.4 index is not a good index for distinguishing the CP-type from the EP-type events.

As aforementioned, the pattern correlation between the fitted curves that characterize the CP- and EP-type SSTAs is −0.07, which is far weaker than the pattern correlation of 0.2 between the two spatial patterns using the regression–EOF method proposed by Kao and Yu (2009). Furthermore, during the study period, we notice that the correlation between $I_{CP}$ and $I_{EP}$ is 0.17, which is also weaker than the correlation coefficient of 0.35 between the KaoCP and KaoEP indexes. These results suggest that the two new indexes $I_{CP}$ and $I_{EP}$ are almost independent of each other in sense of statistics. This is very interesting. It would be very convenient for our better investigating the CP and EP types of SSTA events independently.
4 | CIRCULATION ANOMALIES RELATED TO CP- AND EP-TYPE EVENTS

Two new indices independent of each other are constructed, respectively, for summertime CP- and EP-type ENSO events. Based on the new indices, the air–sea interactions in association with variations of these two types of SSTA pattern can be explored. Figure 4 is presented for the SSTA pattern regressed on these two indices whereas Figure 5 is for the relevant climate anomalies in tropical Pacific.

It should be clarified that the summer SSTA variations in tropical Pacific are indeed dominated by the CP- and EP-type SSTA events. In fact, 20.44% (18.80%) of total variances of SSTA in equatorial Pacific (120°E–80°W, 5°S–5°N) (tropical Pacific [120°E–70°W, 20°S–20°N]) can be explained by $I_{CP}$. Similarly, in regions (120°E–80°W, 5°S–5°N) and (120°E–70°W, 20°S–20°N), the $I_{EP}$ can, respectively, explain 63.91 and 44.39% of total SSTA variances. Because indexes $I_{CP}$ and $I_{EP}$ are almost independent of each other, the portion of total SSTA variances explained by both the $I_{CP}$ and $I_{EP}$ indexes are approximately 84.35 and 63.19% in equatorial Pacific and tropical Pacific regions, respectively. We do the similar calculations for KaoCP and KaoEP indexes. It is found that 19.59 and 22.79% of total SSTA variances in above two regions can be explained by KaoCP and 42.49 and 31.60% by KaoEP. As KaoCP and KaoEP correlate with each other significantly though weak, the sum of portion of SSTA variance explained by KaoCP and KaoEP is 62.08% (54.39%) in equatorial Pacific (tropical Pacific).

The SSTA patterns related to the $I_{CP}$ and $I_{EP}$ indexes indeed demonstrate the signatures of CP- and EP-type SSTA distributions. In Figure 4a, the strongest anomalies in association with $I_{CP}$ appear, as we expect, in central equatorial Pacific, showing the reversal of zonal gradient of SSTA around 160°W at equator. In the Maritime Continent (MC), when $I_{CP}$ is in its positive (negative) phase, the SSTAs are negative (positive). However, in Figure 4b the strongest anomalies of SST occur in region for Niño1+2, displaying the almost same signed SSTA gradient at equator. It is also observed that there exist negative (positive) SSTA in both MC and western tropical Pacific when $I_{EP}$ is in its positive (negative) phase.

The corresponding circulation anomalies near ocean surface for both types of SSTA events show Gill–Matsuno-type response of the atmosphere to the oceanic forcing (Matsumo, 1966; Gill, 1980). The differences in the near-surface circulation anomalies between CP and EP types of events are mainly found in the locations of cyclonic circulation pairs north and south of equator. In Figure 4a, there observe the cyclonic circulation pair around points (150°W, 5°N) and (130°E, 5°S) in CP-type events whereas in EP-type events the pairs around points (125°E, 5°S) and (90°W, 20°S).

Both the summertime rainfall and near-surface air temperature anomalies in tropical regions are significantly and differently affected by the CP and EP types of SSTA events. It is seen in Figure 5a that, when $I_{CP}$ is in its positive phase, two Walker cells are well defined in equatorial Pacific with anomalous ascent of air over central equatorial Pacific and anomalous descent of air over MC and oceanic region west

| Indices | Niño3.4 | Niño4 | C | KaoCP | EMI | TNI | Niño1+2 | Niño3 | E | KaoEP | $I_{EP}$ |
|---------|------|----|--|----|---|----|-------|-----|--|-----|--------|
| $I_{CP}$ | 0.69 | 0.84 | 0.86 | 0.79 | 0.75 | −0.66 | 0.10 | 0.38 | −0.08 | −0.19 | 0.17 |
| $I_{EP}$ | 0.77 | 0.48 | 0.37 | 0.12 | −0.27 | 0.42 | 0.96 | 0.95 | 0.91 | 0.86 | 1.00 |
of Peru, inducing more than normal rainfall over CP whereas less than normal rainfall over MC and oceanic region near Peru. However, when $I_{EP}$ is in its positive phase, only is one anomalous Walker cell well defined along equator with upwards atmospheric motion over region east of 160°E whereas the downwards atmospheric motion over MC region, significantly resulting in more than normal rainfall in most of the equatorial Pacific. The air temperature anomalies as shown in Figure 5e,f are widely affected in tropical region by the CP and EP types of SSTA forcings, which look in consistence with the SSTA patterns as shown in Figure 4a,b. The scenarios are opposite when these indices in their negative phases. These climate anomalies affect by CP- and EP-type SSTA as discussed above are in overall in agreement with known results from different research groups (e.g., Weng et al., 2007; Kao and Yu, 2009; Kug et al., 2009; Takahashi et al., 2011).

5 | SUMMARY

In the present study, based primarily on the different SSTA zonal patterns in the tropical Pacific during the boreal summer, we have developed two SSTA indices including $I_{CP}$ and $I_{EP}$ for CP- and EP-type SSTA events, respectively. Using both these two indices, we are able to capture the main features of the CP and EP types of SSTA variations in spatial and temporal.

It is found that the $I_{CP}$ and $I_{EP}$ are almost statistically independent of each other. The $I_{CP}$ and $I_{EP}$ can co-explain 84.35% (63.19%) of total variance of summer SSTA in equatorial Pacific (tropical Pacific). In boreal summer, the EP-type SSTA events vary mainly on inter-annual timescales whereas CP-type events do mainly on both inter-annual and inter-decadal timescales. Index Niño3.4 almost equally mixes the signals of CP and EP types of SSTA events, indicating that this Niño3.4 is not a good index for describing CP or EP type of SSTA signal only.

Spatial patterns of both CP and EP types of SSTA variations are successfully captured as expected when we perform the correlation or regression analysis of SSTA by employing these two indices. For CP-type events, stronger positive (negative) SST anomalies are observed in central tropical Pacific with weaker SSTA in MC region and eastern equatorial Pacific during positive (negative) of $I_{CP}$. For EP-type events, the stronger SSTAs appear in eastern equatorial Pacific and Peruvian coastal region with weaker SSTAs in MC and western equatorial Pacific regions. Because of these different patterns of CP-type and EP-type SSTA, the atmosphere responds correspondingly to SSTA forcing, inducing different types of anomalous patterns of

![Figure 4](image-url)
circulations in horizontal, zonal-vertical circulations, rainfall, and near-surface air temperatures.

The main features captured by using indices $I_{CP}$ and $I_{EP}$ for boreal summer SSTA events in tropical Pacific, as concluded above, are in consistent with known results about CP and EP type of ENSO events in wintertime. However, as the most of annual rainfall occurs in summer in the Northern Hemisphere (Guan et al., 2003; Guan and Yamagata, 2003), it is so important for us to understand the phenomena, influences, and the mechanisms of the CP and EP type of summer SSTA variations. This pair of indices serves this purpose.
Technically, these two indices are easily to be obtained by just doing arithmetic calculations using Equations A3 and A4 and then being multiplied by the absolute values of regional mean SSTA as per Equations 2 and 3. Of course, the regression coefficients in Table 2 should be incorporated into these equations. For monitoring the SSTA pattern instantly and quantitatively, we can calculate these two indices for the coming summer with no need to consider the observations of past summers. This is not as complicated as doing EOF and other similar analysis.

As index $I_{CP}$ is almost independent of index $I_{EP}$, these pair of indexes can be used to linearly remove/isolate the influences of CP-/EP-type SSTA on summer circulation and climate anomalies outside tropical Pacific. In this way, the influences of CP-/EP-type SSTA on summer circulation and pair of indexes can be used to linearly remove/isolate the total variance of SSTA (Ashok et al., 2007; Li et al., 2010; Marathe et al., 2015) as per EOF analysis, the intensities and occurrences of El Niño Modoki events are not large enough to affect the CP-type SSTA pattern in recent years. More than this, many studies demonstrate that in both the composite and regression analyses, when a CP-type El Niño occurs, no negative SSTA are observed in the equatorial Pacific near the coast of South America (Kao and Yu, 2009; Yeh et al., 2009; Yu and Kim, 2010; Ren and Jin, 2011). So, the ENSO Modoki can be considered as a special case of CP-type ENSO. In other words, the ENSO Modoki is a special phenomenon that deserves more deep investigations because its signature is different from the regular CP-type ENSO events.

Although there are a lot of studies on CP and EP types of ENSO and related indices are successfully proposed before as aforementioned above, whether the similar indexes for boreal spring and fall can be constructed is still needed to examine. More than this, the mechanisms behind the formations of CP and EP type of SSTA events in any of the four seasons deserve deep investigations in the future.

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APPENDIX: COMPUTING METHOD OF PATTERN CORRELATIONS

Let $T_{Sa}$ denote the SSTA averaged over $5^\circ$S–$5^\circ$N, which varies with both time and longitude. The zonal mean of $T_{Sa}$ over $DP : [\lambda_0, \lambda_E]$ is denoted by $[T_{Sa}]_{DP}$. Then the difference of $T_{Sa}$ from $[T_{Sa}]_{DP}$ is obtained as

$$T^*_a = T_{Sa} - [T_{Sa}]_{DP}$$ \hspace{1cm} (A1)

Similarly, we easily obtain the zonal difference of $F_{CP}$ and $F_{EP}$ from their zonal means as follows:

$$F^*_{CP}(\lambda) = F_{CP}(\lambda) - [F_{CP}]_{DP}$$ \hspace{1cm} (A2)

$$F^*_{EP}(\lambda) = F_{EP}(\lambda) - [F_{EP}]_{DP}$$ \hspace{1cm} (A3)

Then the pattern correlations between SSTA and $F_{CP}(\lambda)$, and between SSTA and $F_{EP}(\lambda)$ are obtained, which can be expressed for the gridded data in spatial discrete form as

$$r_{CP}(t) = \sum_{i=1}^{M} T^*_{Sa}(t) F^*_{CP} / \left[ \sum_{i=1}^{M} T^2_{Sa}(t) \sum_{i=1}^{M} F^2_{CP} \right]^{1/2}$$ \hspace{1cm} (A4)

$$r_{EP}(t) = \sum_{i=1}^{M} T^*_{Sa}(t) F^*_{EP} / \left[ \sum_{i=1}^{M} T^2_{Sa}(t) \sum_{i=1}^{M} F^2_{EP} \right]^{1/2}$$ \hspace{1cm} (A5)

where $i = \Gamma,M$ with first grid point at $\lambda_0$ and the Mth grid point at $\lambda_E$. 

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