Asymmetric Features for Two Types of ENSO
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ABSTRACT
There are two types of ENSO, namely, the eastern Pacific (EP) ENSO that is characterized by the warmest (coldest) SST anomalies in the eastern equatorial Pacific, and the central Pacific (CP) ENSO whose maximum (minimum) SST anomalies are over the central equatorial Pacific. Asymmetric features of SST anomalies for the EP and CP types of ENSO events and their possible mechanisms were analyzed by using a variety of data during the period 1961–2010. The responses of atmospheric circulation to the two types of ENSO were also discussed. The results showed asymmetric features of SST anomalies in terms of spatial and temporal distributions and intensity. Although the dominant mechanisms differed at both development and decay stages, the oceanic vertical advection played a key role in the asymmetric intensity of the two ENSO events. In addition, both local and remote atmospheric responses showed strong asymmetric signals, which were consistent with the asymmetric distribution of SST anomalies. The asymmetric atmospheric responses in EP-ENSO (CP-ENSO) were similar to those associated with EP-El Niño (CP-La Niña). The intensity of asymmetric responses related to the EP-ENSO was much stronger than that related to the CP-ENSO.

Key words: EP-ENSO, CP-ENSO, air-sea coupled features, asymmetry
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1. Introduction
ENSO is the most significant large-scale air-sea interaction in the global climate system, which is also recognized as one of the hopeful means to improve seasonal prediction. Climate scientists and governments around the world concern the ENSO due to its crucial influence on the global climate (van Loon and Madden, 1981; Ropelewski and Halpert, 1987, 1996; Trenberth and Caron, 2000). Many studies have illustrated the complexity and diversity of ENSO events (Neelin et al., 1998; Trenberth and Stepaniak, 2001; Jin et al., 2003; Bejaron and Jin, 2008; Zhang et al., 2009, 2012). In the last 20 years, a warming phenomenon different from the conventional El Niño occurred frequently over the equatorial Pacific, with its maximum anomalous SST located over the central equatorial Pacific rather than eastern equatorial Pacific (Yeh et al., 2009; Lee and McPhaden, 2010). It is known that an El Niño event is typically characterized by anomalous warm SST located over the eastern equatorial Pacific while anomalous cold SST is located over the western equatorial Pacific. However, the new type of El Niño usually has positive SST anomalies (SSTAs) over the central equatorial Pacific, together with weak warm SSTAs over the eastern equatorial Pacific and negligible cold SSTAs over the western Pacific, which is named as the “dateline El Niño,” “El Niño Modoki,” “central Pacific El Niño” (CP-El Niño), or “warm pool El Niño,” while the classical El Niño is called “conventional El Niño,” “eastern Pacific El Niño” (EP-El Niño), or “cold tongue El Niño” (Larkin and Harrison, 2005; Ashok et al., 2007; Kao and Yu, 2009; Kug et al., 2009; Ren and Jin, 2011).

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Correspondingly, Kao and Yu (2009) classified La Niña events into EP and CP types based on empirical orthogonal function (EOF) analysis. Using the Niño3 and Niño4 indexes, Yuan and Yan (2013), Wang et al. (2014), and Zhang et al. (2015) also categorized La Niña events into two types according to the spatial distribution of SSTAs in their mature phases. In this study, the two types of ENSO are described as EP-El Niño (EP-La Niña) and CP-El Niño (CP-La Niña), respectively. Consistently, these two types of ENSO events can be identified by their zonal locations of SSTAs despite of disagreement on their definitions and names.

Though some researchers had doubts about the existence of the new type of El Niño, and about the independence of these two types of El Niño (Trenberth and Stepaniak, 2001; Trenberth et al., 2002; Takahashi et al., 2011; Karnauskas, 2013), many studies showed marked differences between these two types in terms of physical mechanisms and climate impacts. For the EP-El Niño, its initiation and developing processes are mainly influenced by changes in thermocline and surface winds over the equatorial Pacific. In contrast, the CP-El Niño tends to start, develop, and decay over the central equatorial Pacific, as a local air-sea coupling (Kug et al., 2009; Ren et al., 2012). Moreover, air-sea coupled processes of these two types of El Niño can impact the global climate via teleconnection patterns, including distinct climate responses in the countries and regions around the Pacific Ocean such as East Asia (Wang et al., 2000; Zhang et al., 2011, 2013, 2014; Yuan and Song, 2012), Southeast Asia (Feng et al., 2010b), America (Weng et al., 2007, 2009; Zhang et al., 2012), South America (Tedeschi et al., 2012), Australia (Taschetto et al., 2010), and even Africa and Europe (Moron and Ward, 1998). In addition, the two types of El Niño exert influences on the SST over the Indian Ocean (Kao and Yu, 2009), the tropical cyclones over the western North Pacific (Chen and Tam, 2010) and North Atlantic (Kim et al., 2009), and the storms over the Southern Hemisphere (Ashok et al., 2009). On the other hand, the impacts of the two types of La Niña remain uncertain. Some studies argued that the zonal shift of anomalous SST pattern in a cold event is not significant compared to a warm event (Kug et al., 2009; Kug and Ham, 2011; Ren and Jin, 2011). However, many recent studies suggested that La Niña events need to be separated into two types based on their regional dynamics and extratropical teleconnections. In some studies, La Niña events can be classified into two types regarding their SST patterns, anomalous ocean current, and dynamic features (Shinoda et al., 2011; Zhang et al., 2015). Meanwhile, other studies found that the two types of La Niña are associated with different regional climate responses. For example, both observational and numerical studies have confirmed that the two types of La Niña have roughly opposite impacts on the location of tropospheric jet stream and the phase of the North Atlantic Oscillation (NAO) (Wang et al., 2014; Zhang et al., 2015). Also, the two types of La Niña events can lead to different anomalous climate states over Australia and Brazil (Cai and Cowan, 2009; Tedeschi et al., 2012). It was also found that climatic impacts of the two types of ENSO events are different in their warm and cold phases. With respect to the Australian summer rainfall, Cai et al. (2010) found that the EP-ENSO-rainfall relationship is asymmetric, that is, the southeast Queensland summer rainfall increases with La Niña amplitude, while no significant change is found in the El Niño-related rainfall. Similarly, an asymmetric rainfall teleconnection pattern also exists in CP-ENSO. As suggested by Karori et al. (2013), the boreal summer rainfall over the Yangtze River valley and South China also shows asymmetric features under the two types of ENSO. Taking summer rainfall over South China for example, it has a significant negative relationship with EP-El Niño and a positive relationship with CP-El Niño, while it does not correlate with both types of La Niña events. Therefore, climatic responses to the two types of ENSO not only are closely related to the ENSO type but also depend on the ENSO phase.

Climate responses to the ENSO are sensitive to the location and intensity of SSTAs. Thus, the response to the warm phase is not opposite of that to the cold phase because of the asymmetry of ENSO; and a La Niña even cannot be regarded as an op-
posite event of El Niño. In practice, especially in terms of seasonal prediction, treating ENSO as a linear system would lose some important signals. Previous studies have revealed that the El Niño events are always stronger than the La Niña events (Kang and Kug, 2002; An and Jin, 2004; Okumura and Deser, 2010), indicative of their asymmetries in amplitude. Furthermore, researchers have explored the asymmetric features between extremely strong and weak ENSO events (Dommenget et al., 2013; Frauen et al., 2014), including their spatial pattern, phase transition, duration, and propagation (Zhang et al., 2009; Dommenget et al., 2013; Yeh et al., 2014), together with their possible causes, such as the nonlinear dynamic heating (An and Jin, 2004; Su et al., 2010), the atmospheric nonlinear responses (Kang and Kug, 2002), the effect of tropical instability waves (Jochum and Murtugudde, 2004), the adjustment of Madden–Julian Oscillation (MJO) (Kessler and Kleeman, 2000; Li et al., 2014), and the biological-physical feedback (Timmermann and Jin, 2002).

The EP-El Niño dominated over the equatorial Pacific prior to the 1990s, while the CP-El Niño occurred more frequently in the recent 20 years (Kim et al., 2009; Dou, 2011; Zhang et al., 2011, 2012, 2014; Xu et al., 2012; Yeh et al., 2014). The occurrence of these two types of El Niño exhibits significant interdecadal variation, as well as a stronger EP-El Niño than CP-El Niño. Although many studies focused on the asymmetry of the ENSO, detailed analysis for the asymmetric features related to the two types of ENSO events and their possible mechanisms is still needed. In this study, we compare asymmetric atmospheric responses to the two types of ENSO and explore their possible mechanisms, in order to gain a further understanding of the mechanisms of the ENSO events.

2. Data and method

The datasets used in this study are as follows: 1) monthly SST from the extended reconstructed SST (ERSST.V3b; Smith et al., 2008) and monthly precipitation from the precipitation reconstruction (PREC; Chen et al., 2002), for the period of 1961–2010 provided by the NOAA; 2) monthly mean 850-hPa wind and 500-hPa geopotential height fields for the same period of 1961–2010 from the NCEP/NCAR reanalysis (Kalnay et al., 1996); 3) the interpolated outgoing longwave radiation (OLR) for the period from June 1974 to December 2010 from NOAA (Liebmann and Smith, 1996); 4) oceanic subsurface temperatures (Simple Ocean Data Assimilation, SODA2.0.2–4) for the period of 1961–2007 from the University of Maryland (Carton et al., 2000); 5) monthly surface heat fluxes derived from the NCEP/NCAR reanalysis for the period of 1961–2007 (Kalnay et al., 1996); and 6) monthly mean rainfall at 160 stations for the period of 1961–2010, available from the China Meteorological Administration.

In this study, the winter (DJF) is regarded as the mature period of El Niño (La Niña) event. Anomalies of each variable are defined as the deviation from the seasonal mean based on the climatology from 1961 to 2010, except for the anomalies of OLR, which are calculated based on the climatology from 1975 to 2010. The heat budget equation diagnosis is based on the data from 1961 to 2007. A composite analysis method is applied to all the variables for the two types of ENSO events. Moreover, taking the sum of El Niño and La Niña events as the asymmetric component is widely used (e.g., Okumura and Deser, 2010; Wu et al., 2010; Karori et al., 2013), and the Student $t$-test is used.

At present, there are many indexes defining ENSO events. Previous studies classified these two types of ENSO events by using the EOF method. However, An and Jin (2004) pointed out that this linear method cannot describe the asymmetric features between El Niño and La Niña events. In addition, some studies utilized Niño3 index and El Niño Modoki index (EMI) to depict the two types of ENSO events. According to Ashok et al. (2007), $\text{EMI} = 1.0T_A - 0.5T_B - 0.5T_C$, where $T_A$, $T_B$, and $T_C$ represent the area-averaged SSTAs over the regions A (10°S–10°N, 165°E–140°W), B (15°S–5°N, 110°–70°W), and C (10°S–20°N, 125°–145°E), respectively. Zhang et al. (2015) mentioned that despite the fact that the EMI can well characterize CP-El Niño, it cannot effec-
tively differentiate the two types of La Niña events. By comparing the differences among a variety of ENSO indexes and their capacities to describe the seasonal-locking features for these two types of ENSO, Cao (2011) suggested that the Niño3 index is the best one to identify the EP events while the Niño4 index is much better for identifying the CP events. Motivated by Kug et al. (2009) that proposed the two types of ENSO events be distinguished by comparing Niño3 and Niño4 indexes together with their relative intensity, Ren and Jin (2011) put forward two new Niño indexes in combination with Niño3 and Niño4 indexes based on a simple linear method, and these two new Niño indexes can be used to identify these two types of events, but not suitable for separating the La Niña events into two types. Hence, the categorization for these two types of ENSO events, especially for the La Niña events, not only relies on Niño indexes but also should be combined with SSTA pattern.

Referring to the definitions of the two types of El Niño events from Kug et al. (2009), Yeh et al. (2009) and Zhang et al. (2011) and the definitions of the two types of La Niña events from Wang et al. (2014) and Zhang et al. (2015), the two types of ENSO events in this study are identified based on the National Climate Prediction Center (NOAA CPC) definition of ENSO events in combination with SSTA pattern in the mature period. First, according to the CPC’s definition of El Niño and La Niña events [considering 3-month running mean Niño3.4 index (5°S–5°N, 120°–170°W), El Niño (La Niña) events are identified when the winter SSTAs are higher than (less than) 0.5°C (−0.5°C) for five consecutive months, 17 El Niño events and 16 La Niña events are selected during the period 1961–2010. Second, comparing the absolute values of winter normalized Niño3 index (5°S–5°N, 150°–90°W) and Niño4 index (5°S–5°N, 160°E–150°W), respectively. If the Niño3 index is greater than the Niño4 index, the corresponding event is defined as EP-El Niño (or EP-La Niña); otherwise, it is referred to CP-El Niño (or CP-La Niña). According to Wang et al. (2014) and Zhang et al. (2015), three La Niña events (i.e., 1970/1971, 1999/2000, and 2007/2008) are characterized by westward-propagating negative SSTAs in their peak phases; it is difficult to categorize them in terms of air-sea coupling features. Thus, they are removed from the following composite analysis; the 2008/2009 La Niña event is also removed for its short duration. In addition, the 1968/1969 and 1969/1970 events are regarded as one El Niño event; so are the 1986/1987 and 1987/1988 events, and the stronger events in 1968/1969 and 1986/1987 are chosen as the representatives of these two processes, respectively. Similarly, the stronger 1975/1976 event is taken as a representative of the long-lasting 1974/1975 and 1975/1976 La Niña events. Furthermore, comparing the composite results before and after removing these three events with long durations, it is found that the influences of removing these events on the results are negligible. The selected events for these two types of ENSO are listed in Table 1. The La Niña events are consistent with those in Wang et al. (2014) and Zhang et al. (2015); and the El Niño events are similar to those in the previous studies despite of some minor differences that do not affect our conclusions.

### 3. SST anomalies and associated asymmetric features

Figure 1 shows the composite SST anomaly patterns for the two types of ENSO events and their asymmetric features. As mentioned before, at the mature stage of EP-El Niño, marked positive SSTAs appear over the eastern equatorial Pacific with maximum SSTAs (greater than +2.0°C) located in the Niño3 region, whereas negative SSTAs over the western equatorial Pacific, and subtropical North and South Pacific (Fig. 1a). In contrast, negative SSTAs are limited to

| Table 1. Two types of ENSO events during 1961–2010 |
|-----------------------------------------------|
| Eastern Pacific (EP) type | Central Pacific (CP) type |
| El Niño | 1965/1966, 1972/1973, 1976/1977, 1982/1983, 1986/1987, 1991/1992, 1997/1998 | 1963/1964, 1968/1969, 1977/1978, 1994/1995, 2002/2003, 2004/2005, 2006/2007, 2009/2010 |
| La Niña | 1964/1965, 1971/1972, 1984/1985, 1995/1996, 2005/2006 | 1973/1974, 1975/1976, 1983/1984, 1988/1989, 1998/1999, 2000/2001 |
the eastern equatorial Pacific near the Niño3 region during EP-La Niña with a relatively weak intensity (−0.8°C), which is about half of that during El Niño. Meanwhile, the warm SSTAs over the western equatorial Pacific are not significant, and anomalous warming only occurs near the west coast of South America (Fig. 1c). Therefore, the asymmetric features of EP-ENSO are mainly characterized by the differences between the intensity and location of El Niño and La Niña, shown as positive SSTAs over the eastern equatorial Pacific extending from the west coast of South America to the east of the dateline along the equator, and the negative anomalies over the western equatorial Pacific, western North Pacific, and the subtropical central South Pacific (Fig. 1e).

Compared with the EP-ENSO, the anomalous SST centers related to the CP-ENSO event shift westward. It can be clearly seen that positive SSTAs shift to the central equatorial Pacific, with maximum SSTAs (greater than +1.2°C) in the Niño4 region (Fig. 1b). Meanwhile, the negative SSTAs over the western Pacific are not significant but with an anomalous cooling in the subtropical South Pacific. Like the CP-El Niño, the negative SST center of CP-La Niña also moves westward to the central equatorial Pacific Ocean with a relatively stronger intensity (up to −1.6°C). In addition, significant positive SSTAs appear over the western equatorial Pacific and in the subtropical North and South Pacific, together with the negative SSTAs over the central equatorial Pacific, forming a horseshoe-like pattern in the Pacific similar to the distribution of EP-El Niño in the equatorial Pacific (Fig. 1d). When CP-El Niño and CP-La Niña are compared, it is clear that the asymmetric component of the CP-ENSO is mainly characterized by negative SSTAs near the west coast of North and South
America extending westward along the equator, and positive SSTAs in the western North Pacific as well as subtropical central North and South Pacific (Fig. 1f). In general, the asymmetric distribution of SST during the EP-ENSO is similar to that during the EP-El Niño, while the asymmetric distribution of SST during the CP-ENSO is similar to that during the CP-La Niña.

The time-longitude cross-section of SSTAs over the equatorial Pacific are shown in Fig. 2. For the EP-El Niño event, SSTAs appear in the eastern equatorial Pacific in spring and then propagate westward, but with positive SSTAs first emerge in the central and western equatorial Pacific (near the dateline). Some studies have pointed out that the propagation feature of El Niño experienced an abrupt decadal change in the late 1970s, with its propagation direction switching from westward to eastward (Guilyardi, 2006; Ren and Jin, 2011). Their associated mechanisms, however, are still not well understood. EP-El Niño reaches its mature phase in the boreal winter, with its maximum SSTA center near 120°W and significant negative SSTAs over the western Pacific (Fig. 2a). Then, it slowly decays in the following spring and its positive SSTAs are even maintained in the late spring and early summer of the next year. The negative SSTAs in the eastern equatorial Pacific for EP-La Niña, which is the cold episode of EP-ENSO, are almost opposite to those for El Niño. However, the SSTAs propagate westward in the developing and decay stages with short durations. What is more, the early SSTAs signal of EP-La Niña appears in the eastern Pacific during the winter, while it ends quickly in the following early spring after the mature stage (Fig. 2c). Weak positive SSTAs over the western equatorial Pacific are dominant only in the mature stage. Comparing the warm and cold events during the EP-ENSO, it can be concluded that due to the SST differences between the amplitudes of El Niño and La Niña, significant positive SSTAs appear in the eastern equatorial Pacific, while negative SSTAs appear in the western equatorial Pacific during the current summer to the following spring. In addition, the notable negative SSTAs over the eastern equatorial Pacific in winter are likely associated with the accumulation of cold water there before the EP-El Niño appears (Fig. 2e).

Different from the EP-El Niño, the CP-El Niño event usually initiates, develops, and decays locally (Fig. 2b), consistent with previous studies (Kao and Yu, 2009; Ren et al., 2012; Zhang et al., 2014). During
the CP-El Niño, positive SSTAs first appear in the central Pacific (west of the dateline), then spread eastward in autumn and winter, and decay westward in the following spring until reversing its sign in the eastern equatorial Pacific. Meanwhile, the positive SSTAs in the western Pacific extend eastward, with the maximum SSTA center limited near the dateline. Similar to the CP-El Niño, the CP-La Niña event also propagates eastward with its anomalous cold center limited to the central equatorial Pacific, which differs from the EP-La Niña. However, it is noticeable that the CP-La Niña has a longer duration and stronger intensity compared to the CP-El Niño. In addition, its significant cold anomalies over the whole central and eastern equatorial Pacific Ocean are maintained even in the following summer (Fig. 2d), which is confirmed by Fig. 2f. On the one hand, due to the differences between the intensities of CP-El Niño and CP-La Niña events, the asymmetric features of CP-ENSO are shown as significant negative SSTAs in the central-eastern equatorial Pacific, together with strong positive anomalies in the western equatorial Pacific during its initiation and development periods. On the other hand, the asymmetric component of the CP-ENSO during the decay period is still characterized by remarkable negative SSTAs over the central-eastern equatorial Pacific due to the discrepancy between the persistence of the two events (Fig. 2f).

To verify the asymmetry of CP-ENSO in its persistence and intensity, the temporal evolutions of the two types of ENSO events are shown in Fig. 3. Standardized Niño3 and Niño4 indexes are used to represent EP-ENSO and CP-ENSO events, respectively. In comparison, the EP-El Niño event persists much longer and even lasts to the following summer, while the EP-La Niña event rapidly demises in the early spring of the following year. CP-El Niño signal damps in the early summer of the next year, while the CP-La Niña signal persists to the following autumn and even winter. In addition, the intensity difference between the two types of ENSO can be clearly seen from Fig. 3. The EP-El Niño event is much stronger, with its amplitude up to 2 standard deviations, than the EP-La Niña event regarding the intensity, while the intensity of EP-La Niña is only about half of the EP-El Niño (Fig. 3a). The intensity of CP-El Niño is about 1.5 standard deviations, which is weaker than that of EP-El Niño, while the strength of CP-La Niña is close to –2 standard deviations (Fig. 3b), which is much stronger than that of the EP-La Niña or the CP-El Niño event. However, the intensity difference of the CP-ENSO is only about 0.5 standard deviations, weaker than that of the EP-ENSO.

4. Heat budget

In this section, we analyze the various dynamical processes of ENSO based on a heat budget equation for mixed layer temperature, and try to understand the possible mechanisms by which the associated SSTA asymmetries for the two types of ENSO are maintained. The heat budget equation (Zhang et

![Fig. 3. TEMPORAL EVOLUTIONS OF (A) COMPOSITED NORMALIZED Niño3 INDEX DURING EP-ENSO EVENTS, AND (B) COMPOSITED NORMALIZED Niño4 INDEX DURING CP-ENSO EVENTS. NUMBER 0 IN THE PARENTHESES DENOTES THE OCCURRENCE YEAR, AND NUMBER 1 DENOTES THE FOLLOWING YEAR.]
al., 2013) is as follows:

\[
\frac{dT_a}{dt} = -u_a \frac{\partial T_a}{\partial x} - u_a \frac{\partial T_c}{\partial x} - u_a \frac{\partial T_a}{\partial y} - v_a \frac{\partial T_a}{\partial y} - H(w) \left( -v_c \frac{\partial T_a}{\partial z} + w_c \frac{\partial T_a}{\partial z} \right) + \frac{Q_a}{\rho_0 c_p H} + R, \tag{1}
\]

where \( T, u, v, \) and \( w \) denote the mixed-layer (0–45 m) SST, zonal, meridional, and vertical current velocities, respectively. Subscript \( c \) represents the climatology monthly mean, and subscript \( a \) denotes anomalies with respect to the climatology; \( Q_a \) represents anomalous net sea surface heat flux, including longwave and shortwave radiation, latent and sensible heat fluxes; \( \rho_0 \) and \( c_p \) indicate the density and heat capacity of seawater, respectively; \( H \) is the mixed layer depth; \( R \) is the residual term, including small-scale processes and dissipation. We only consider the effect of lower-layer ocean temperature on the upper-layer ocean temperature here. Therefore, the function \( H(w) = 1 \) for \( w > 0 \) and \( H(w) = 0 \) for \( w < 0 \).

Only SST general trend and several large terms are discussed here by considering the development and decay stages for the two types of ENSO, including zonal advection \((-u_a \frac{\partial T_c}{\partial x})\), meridional advection \((-v_a \frac{\partial T_a}{\partial y})\), vertical advection \((-w_c \frac{\partial T_a}{\partial z})\), and heat flux term \( \left( \frac{Q_a}{\rho_0 c_p H} \right) \). According to the definition of Kug et al. (2010), the development period of an ENSO event is from March to November and the decay period is from February to October of the following year. Due to the different key areas of air-sea coupling for EP- and CP-ENSO events, we focus on the area over the eastern equatorial Pacific (Niño3 region: 3°S–3°N, 150°–90°W) for EP-ENSO and the area over the central equatorial Pacific (Niño4 region: 3°S–3°N, 160°E–150°W) for CP-ENSO.

As shown in Fig. 4a, zonal advection UATC and vertical advection WCTA play major roles in the growth and decay of EP-El Niño over the eastern equatorial Pacific, which is consistent with Kug et al. (2010). In the development stage, vertical advection determined by mean upwelling and anomalous temperature gradient is relatively large, suggesting that the thermocline feedback mechanism is more important in the development process of EP-El Niño than zonal advection. Zonal advection, vertical advection, and other terms reverse their signs from positive to negative during the decay stage, accompanied by EP-El Niño strong discharge process and reversed zonally-averaged heat content. In addition, heat flux (FLUX) remains negative in the evolution, indicating dissipative effect on positive SSTAs in EP-El Niño development process. However, FLUX does not contribute to the negligible magnitude in the decay stage. It is noticeable that the values of meridional advection (VCTA) in the processes of development and decay are relatively large. Suggested by Zhang et al. (2009, 2013), the development and termination of VCTA are in phase with those of the SSTAs. As a result, VCTA
may not play a major role in the growth and decay of ENSO as zonal and vertical advection terms do, and it mainly acts to spread SSTAs poleward through meridional advection. Therefore, VCTA is no use for the corresponding SSTA growth despite of its large value. For this reason, no detailed analysis of VCTA is given further in this paper.

By comparison, the terms in EP-La Niña are almost the same as those in EP-El Niño, but with opposite signs. Zonal and vertical advection terms still dominate the development and decay stages, while heat flux tends to become weak from the development to the decay stages. Nevertheless, the terms in EP-La Niña event are relatively weak, especially in the development stage, with only half of those in EP-El Niño event in terms of magnitude. Meanwhile, zonal advection is relatively crucial during the development and decay stages, which contributes to the phase transition. Interestingly, all the terms are weak during the development stage but become stronger during the decay stage, suggesting that an EP-La Niña event grows slowly but decays fast, which is consistent with Fig. 3a in terms of asymmetric features in temporal revolution. However, EP-El Niño is almost symmetry during its evolution (Fig. 4b).

As for the EP-ENSO asymmetric component (Fig. 4c), the magnitudes of terms tend to decrease from development to termination, except for zonal advection. In addition, the signs of terms in asymmetry component are generally consistent with those in EP-El Niño. For example, both vertical and zonal advections significantly contribute to the evolution of ENSO, but the former is much stronger. Therefore, the asymmetric EP-El Niño-like distribution of SSTAs for the EP-ENSO is mainly attributed to the strong vertical and zonal advections in the temporal evolution, especially for the vertical advection of EP-El Niño event.

In contrast with the EP-El Niño event, the dynamic processes of CP-El Niño are much weaker with only half of the intensity of EP-El Niño, leading to a relatively weaker signal of SSTAs during the peak stage (Fig. 5a). The dynamic feedbacks of their growth and termination are also different. For example, zonal advection dominates the whole process of CP-El Niño, while vertical advection is relatively weak (even close to zero in the decay stage). It is revealed that zonal advection plays a more important role in the CP-El Niño’s evolution instead of vertical advection (Kug et al., 2010). In general, the thermocline in the central equatorial Pacific is deeper than that in eastern equatorial Pacific, resulting in insensitive response of subsurface temperature to the change in thermocline. Therefore, changes in wind and pressure lead to weak anomalous temperature over the central equatorial Pacific. On the other hand, the temperature gradient over the central equatorial Pacific (the transition region of eastern and western Pacific) is quite strong, and eastward ocean current anomaly caused by anomalous pressure field enhances the warm water transport from the western Pacific to the central Pacific, leading to a large increase in SST. When the CP-El Niño demises, the discharge process is weak due to the deep thermocline over the central equatorial...
Pacific. As a result, vertical advection is almost zero and the phase transition of SST is mainly attributed to zonal advection. Note that heat flux also contributes to the termination of ENSO.

Correspondingly, the sign of each term is reversed in the CP-La Niña event, and the magnitude increases, especially in the development stage. Unlike CP-El Niño, vertical advection is relatively large compared to zonal advection during the developing stage of CP-La Niña, which is similar to that of EP-El Niño. During the decay stage, vertical and zonal advections are comparable in magnitude (Fig. 5b). On the other hand, heat flux is almost unchanged in both development and decay stages. Heat flux is out-of-phase with the general trend of SSTAs during the development stage, which acts to damp SSTAs, while it is in-phase with the observed SST tendency in the decay stage to enhance SST warming. Interestingly, due to the asymmetry of the amplitudes of SST trend between the development and decay stages, negative SSTAs require more time to disappear, resulting in a longer duration of CP-La Niña event (Fig. 3b).

Comparing the warm and cold events of CP-ENSO, it is clear that the magnitude of the asymmetric component for CP-ENSO is quite small. What is more, the sign of each term is in accordance with that of CP-La Niña, indicating that CP-ENSO asymmetric pattern of SSTAs is similar to CP-La Niña asymmetric pattern. However, it should be pointed out that the asymmetry in the intensity of CP-ENSO varies with time just like the EP-ENSO but with smaller amplitude, that is, the event is strong in the development stage but weak in the following stage. As vertical advection dominates the whole asymmetric evolution (Fig. 5c), the intensity asymmetry of CP-ENSO can be attributed to vertical advection as well.

As mentioned before, the marine vertical advection is relatively strong in EP-El Niño and CP-La Niña events, which is probably related to their background conditions. When an EP-El Niño event happens, the warm water propagates eastward and the shallow thermocline deepens over the eastern Pacific; thus, strong vertical motion favors the growth of EP-El Niño event. When an EP-La Niña occurs, the thermocline is faintly shoaled due to the shallow thermocline over the eastern equatorial Pacific. Therefore, the change is so diminutive that the marine vertical advection is relatively weak. Similarly, the thermocline over the central equatorial Pacific is much deeper than that over the eastern Pacific. Thus, the deepened thermocline caused by warm water is negligible in the CP-El Niño event, together with weaker vertical motion, while the thermocline tends to shoal remarkably over the central equatorial Pacific during the CP-La Niña. Therefore, the enhanced vertical advection results in stronger CP-La Niña compared to CP-El Niño.

5. Asymmetric atmospheric responses

How does the atmosphere respond to the SST asymmetry for the two types of ENSO? The issue will be discussed in this section.

5.1 Atmospheric responses in the equatorial Pacific Ocean

To examine the atmospheric responses in the equatorial Pacific Ocean, the distributions of winter mean OLR anomalies over the equatorial Pacific for the two types of ENSO are shown in Fig. 6. During EP-El Niño event, OLR anomalies show a significant dipole pattern as enhanced convection over the central-eastern equatorial Pacific near 170°W and suppressed convection over the western equatorial Pacific and subtropical North Pacific (Fig. 6a). The spatial distribution of anomalous OLR in EP-La Niña event is in accordance with that in EP-El Niño but with the opposite signs, shown as suppressed convection over the central-eastern equatorial Pacific but enhanced convection over the western equatorial Pacific, despite of slightly westward-shifted convective centers toward 180° with only half of the amplitude for EP-El Niño event. Nevertheless, no relevant negative OLR anomalies occur over the subtropical North Pacific (Fig. 6c). In general, the asymmetric responses of tropical convection in EP-ENSO correspond to the asymmetric SSTAs, which is similar to the distribution in EP-El Niño but with the signals disappearing over the western equatorial Pacific. The asymmetric responses are mainly characterized by suppressed con-
Convection over subtropical central North and South Pacific and Southeast Pacific, and enhanced convection over the central-eastern Pacific extending northeastward to the south of North America, with the asymmetric convection centers moving eastward to near 150°W (Fig. 6e).

It is quite obvious that anomalous OLR in CP-El Niño is weaker than that in EP-El Niño, and the relevant enhanced convection moves westward along with the SSTAs (Kug et al., 2009). Different from the EP type, an anomalous tripole pattern shows enhanced convection near the dateline and suppressed convection over the eastern equatorial Pacific and over a wide region extending from the western equatorial Pacific to the subtropical central North and South Pacific (Fig. 6b). As for the cold event, suppressed convection in CP-La Niña is also located near the dateline, and enhanced convective activities appear over the western equatorial Pacific and subtropical central South Pacific. However, the tripole pattern of anomalous OLR in CP-La Niña is not significant, especially in the eastern equatorial Pacific, with an enhanced convection center east of 150°W over the subtropical North Pacific (Fig. 6d). Therefore, the asymmetric distribution of anomalous OLR in CP-ENSO is not similar to that in CP-La Niña. Only one suppression center occurs over the western equatorial Pacific, and the asymmetric response is relatively weak in the central equatorial Pacific. Moreover, weak negative OLR anomaly appears in the subtropical central South Pacific, together with a northwest-southeast “− + −” spatial pattern over the eastern equatorial Pacific (Fig. 6f). Note that the convection responses to EP-El Niño and CP-El Niño are quite similar near the dateline. In addition, the locations of anomalous positive centers in the central equatorial Pacific for the two types of La Niña events are more similar, resulting in similar patterns of anomalous precipitation along the equator for the two types of La Niña events (Yuan and Yan, 2013; Yeh et al., 2014), which makes it difficult to distinguish one from the other.

Anomalous SST related to ENSO causes atmospheric circulation responses via anomalous convections, leading to different tropical atmospheric responses. In terms of EP-El Niño-related SST changes, anomalous sea level pressure (SLP) shows a clear seesaw pattern, shown as decreased pressure in the eastern equatorial Pacific and increased pressure in the western equatorial Pacific. Meanwhile, the westerly prevails over the central-eastern equatorial Pacific.
while the easterly prevails over the western Pacific. As a result, anomalous airflow tends to converge and ascend over the eastern equatorial Pacific, but tends to diverge and sink over the western equatorial Pacific, forming a strong anticyclone over the region to the east of the Philippines, that is, the Philippines anticyclone (Fig. 7a). Numerous studies have confirmed that the Philippines anticyclone contributes notably to the climate in East Asia (Zhang et al., 1996; Wang et al., 2000; Feng et al., 2010a; Zhang et al., 2011; Yuan and Song, 2012). In addition, the ascending motion of anomalous Walker circulation is strong and wide over the eastern equatorial Pacific, extending from 120°W to the dateline, in response to the remarkable warming there, while the descending motion is confined over the western Pacific between 120° and 150°E (Fig. 8a). On the contrary, EP-La Niña generally exhibits symmetric configuration in low-level circulation with EP-El Niño, including low pressure in the western equatorial Pacific with easterly wind anomaly over the central-eastern equatorial Pacific and westerly wind anomaly over the western Pacific, and the anomalous cyclone near the Philippines, together with the anti-Walker circulation anomalies over the equatorial Pacific. However, there are still asymmetries in space and intensity, such as the non-significant positive pressure anomalies in the eastern equatorial Pacific, which are weaker than those in EP-El Niño. In addition, the anomalous easterly wind is weak and shifts westward, resulting in the Philippines cyclone to shift westward (Fig. 7c) and weaken descending branch of the anomalous Walker circulation (Fig. 8c), which is consistent with Wu et al. (2010). Since the warm event is strong, the asymmetric component of EP-ENSO shares many features with that of EP-El Niño regarding pressure and wind, except for the positive pressure anomaly center over the western equatorial Pacific turning into north and south parts (Fig. 7e). The asymmetric ascending is mainly located at the middle troposphere near the eastern equatorial Pacific between 150° and 120°W, and the descending branch occurs in the upper troposphere extending from 120° to 150°E (Fig. 8e).

Anomalous SST and its associated enhanced convection are shifted westward in CP-El Niño compared to those in EP-El Niño. Thus, the related SLP and wind fields also show some distinct changes. The SLP anomalies in the eastern equatorial Pacific are not significant and the negative SLP anomalies move to the middle of the subtropical South Pacific. In addition, the easterly wind anomaly appears over the eastern and western equatorial Pacific, while westerly wind anomaly is limited to the central equatorial Pacific.

Fig. 7. As in Fig. 6, but for SLP anomalies (shading; hPa) and 850-hPa wind anomalies (vector; m s$^{-1}$). Only the velocity greater than 1 m s$^{-1}$ is shown.
What is more, the Philippines anticyclone moves to 10°N, 120°E with a reduced scope and intensity, leading to different climate impacts from those in EP-El Niño (Fig. 7b). The ascending branch of the anomalous Walker circulation is mainly located near 180° while the descending one is located at 120°E over the western equatorial Pacific in the upper troposphere, which is weaker than that in EP-El Niño. Note that the weak descending motion in the lower troposphere east of 90°W over the eastern equatorial Pacific does not pass the t-test (Fig. 8b). CP-La Niña shows symmetry with CP-El Niño, including the
opposite phase of SLP, the westward displacement of anomalous SLP center and the reversed Walker circulation anomalies over the equatorial ocean. Nevertheless, there are also asymmetries in space and amplitude. In terms of SLP, CP-La Niña is out-of-phase with EP-El Niño, characterized by increased pressure in the eastern equatorial Pacific and decreased pressure in the western equatorial Pacific; these opposite patterns are possibly linked to their strong signals. As for the low-level winds, stronger and wider easterly wind anomaly along the equator even extends to the west of 150°E in CP-La Niña compared to CP-El Niño, which further converges with the westerly wind anomaly from the western equatorial Pacific over the maritime continent. Meanwhile, the Philippine cyclone shifts slightly northward compared to that in CP-El Niño (Fig. 7d). On the other hand, the descending motion of the anomalous Walker circulation dominates the central-eastern equatorial Pacific between 180° and 120°W while the ascending motion dominates over the eastern and western equatorial Pacific, forming two anomalous Walker circulations over the equatorial ocean. Although the spatial differences between warm and cold events of CP-ENSO are significant, CP-ENSO does not show dominant asymmetric features in the equatorial wind and SLP fields due to their little differences in intensity. The most notably asymmetric features include positive pressure anomalies and related anticyclone circulation in North Pacific near 30°N, 150°W and weak easterly wind anomaly over the central equatorial Pacific (Fig. 7f). In addition, the asymmetric responses of anomalous Walker circulation are characterized by the anomalous descending motion in the lower troposphere over the central equatorial Pacific near 180° and in the upper troposphere over the eastern Pacific near 120°W, and the weak anomalous ascending motion in the upper troposphere near 70°W. As such, the responses in the western equatorial Pacific disappear. Overall, the asymmetric pattern of CP-ENSO is still similar to the pattern of CP-La Niña (Fig. 8f). Thus, local atmospheric responses to the two types of ENSO show strong asymmetric signals in intensity, which is consistent with the asymmetric distribution of SSTAs. Generally, local convective activities are enhanced due to the strong tropical SST warming, leading to asymmetric intensity in local atmospheric responses.

5.2 Atmospheric responses in the extratropical Pacific Ocean

Tropical heating not only causes local atmospheric responses but also forces atmospheric circulation outside the tropics through teleconnection, affecting the weather and climate in the high latitudes (Hoskins and Karoly, 1981; Wallace and Gutzler, 1981). A strong tropical heating would cause an intense extratropical response; thus, the asymmetric response in the extratropics is similar to that in the tropics. However, when energy spreads outside of the tropics, local responses may be affected by local circulation, especially strong nonlinear wave-current interaction in the midlatitudes; however, the related physical mechanism has not yet been well understood. This mechanism is beyond the scope of this article and is not studied further. When the ENSO happens, the most obvious signals of extratropical atmospheric responses occur over North Pacific and its surrounding areas; thus, the responses over this region are discussed. Atmospheric responses in the Northern Hemisphere during EP-El Niño is shown as decreased SLP in the mid-low latitudes over North Pacific and southeastern United State, together with increased pressure over western Canada, which is the positive phase of the Pacific-North America (PNA) teleconnection pattern. This spatial pattern is a quasi-barotropic structure and associated with an anomalous wave train in the middle troposphere (Fig. 9a). Correspondingly, EP-La Niña shows a negative phase of the PNA but with a relatively weak signal, including a significant positive geopotential height anomaly located at 45°N over North Pacific (Wang et al., 2014), together with weak negative anomalies over western Canada and weak positive anomalies over southeastern United States (Fig. 9c). In general, asymmetric teleconnection pattern of EP-ENSO is similar to that of EP-El Niño, except for negligible anomaly centers over western Canada and the central North Pacific. Meanwhile, a negative geopotential height anomaly center occurs
in the high latitudes over East Asia and a positive one over Southeast Japan; and negative anomalies extend from the northwest of North America to southwestern United States (Fig. 9e).

Similar to EP-El Niño, CP-El Niño is also related to the PNA positive phase but with non-significant negative anomalies over the central North Pacific. Interestingly, atmospheric responses over North America and North Atlantic tend to shift northward compared to those in EP-El Niño; for example, the positive anomaly center over Canada moves north to 65°N (Fig. 9b). Ashok et al. (2007) suggested that the northward shift of positive anomalies over Canada might be related to the adjustment of subtropical and sub-polar jet streams induced by CP-El Niño. Comparing to CP-El Niño, CP-La Niña accompanies with a remarkable negative PNA pattern. However, atmospheric responses to CP-La Niña are much stronger: a significantly southward-shifted positive anomaly center is located over North Pacific, together with an eastward-shifted negative anomaly center over Canada (Fig. 9d). Thus, under the influence of the asymmetric intensity of SSTAs in CP-ENSO, the differences between the warm and cold phases of CP-ENSO are shown as a positive anomaly center over the central North Pacific and two negative anomaly centers to the south and north, respectively, which are similar to those in CP-La Niña. It is noticeable that the positive anomaly center in the high latitudes over North America corresponds to that in CP-El Niño, which may be part of local responses (Fig. 9f).

To further explore the influence of the asymmetry of the two types of ENSO on the extratropical region, composites of winter mean precipitation anomalies over North Pacific and its surrounding land are shown in Fig. 10. It can be seen that negative precipitation anomalies in the western equatorial Pacific extend northeastward to the central North Pacific, resulting in reduced precipitation over a larger region in the EP-El Niño. Moreover, precipitation is increased over Northwest Pacific and southern North America, while deficient precipitation is found along the Okhotsk coast and over central North America and northern South America (Fig. 10a). Correspondingly, EP-La Niña symmetrically leads to positive precipitation anomalies in a small region over the central North Pacific and significant negative precipitation anomalies in Northwest Pacific. However, pre-
cipation anomalies along the Okhotsk coast remain negative during EP-La Niña, and precipitation anomalies over North American continent exhibit the northsouth “– + –” pattern (Fig. 10c). Hence, the asymmetric extratropical rainfall of EP-ENSO mainly has the meridional “– + –” pattern over North Pacific, the negative anomalies along the Okhotsk coast, and also deficient precipitation over northern North America and northern South America, but excessive precipitation over central and southern North America (Fig. 10e).

Different from the EP-El Niño event, CP-El Niño-related anomalous precipitation is relatively weak over a small region, with the maximum values concentrated over the equator. In addition, the spatial pattern of precipitation anomalies over North Pacific and its adjacent land is similar to that in EP-El Niño, including reduced precipitation over the central North Pacific and northern South America, while increased rainfall over Northwest Pacific. However, negative precipitation anomalies are more dispersed in the central North Pacific. What is more, precipitation is also decreased over western Canada under the influence of CP-El Niño (Fig. 10b). On the other hand, the distribution of anomalous precipitation of CP-La Niña is similar to that of CP-El Niño, including increased precipitation in the central North Pacific and northern South America, and reduced rainfall in Northwest Pacific. Nevertheless, responses of precipitation are more significant over the central North Pacific and North America, especially in southern North America where precipitation is significantly reduced, and the impact is relatively weak over East Asia (Fig. 10d). Overall, the asymmetric precipitation distribution of CP-ENSO shows the north-south “+ –” structure over North Pacific, which is similar to that of CP-La Niña and is opposite to that of EP-ENSO (Fig. 10f). In addition, deficient precipitation dominates East Asian and North American continents, especially in the Sea of Okhotsk and in northwestern and southwestern North America.

To examine asymmetric responses to the two types of ENSO in detail, Fig. 11 shows the spatial distributions of anomalous precipitation in China. Affected by two different circulation patterns of ENSO, especially by the anomalous Philippines anticyclone (cyclone) over Northwest Pacific, distinct patterns of anomalous precipitation appear over China. In the EP-El Niño event, the southwesterly wind anomaly from the anomalous anticyclone to the east of the

**Fig. 10.** As in Fig. 6, but for precipitation anomalies (mm day$^{-1}$).
Philippines dominates South China, whereas Northeast China and the Hetao area (located in the upper reaches of the Yellow River) are controlled by anomalous northerly wind (Fig. 7a). As a result, precipitation is increased in South China and is reduced in the Hetao area and Northeast China during winter. When EP-La Niña occurs, anomalous easterly wind is weakened over China, together with the southwestward-shifted Philippines cyclone (Fig. 7c). Thus, the impact of EP-La Niña on winter precipitation is not significant, and only weak negative anomalies occur in Southwest China (Fig. 11c). As concluded before, the asymmetric component of EP-ENSO is the same as that of EP-El Niño regarding wind and pressure (Fig. 7e). Thus, winter precipitation responses to the asymmetry of EP-ENSO are characterized by negative anomalies in Central and Northeast China and positive anomalies in South China, which are consistent with that of EP-El Niño (Fig. 11e).

It is noticeable that the Philippines anticyclone in the CP-El Niño event moves to 10°N, 120°E, compared to that moves to 12°N, 135°E, in the EP-El Niño

![Fig. 11. As in Fig. 6, but for precipitation anomalies (mm) over China. Shadings from light to dark indicate the 80%, 90%, and 95% confidence level, respectively.](image-url)
event. Although the range is smaller and the intensity is much weaker, the southwesterly wind anomaly along the anomalous anticyclone still dominates East China (Fig. 7b), resulting in significantly increased precipitation there (Fig. 11b). When CP-La Niña occurs, the Philippines cyclone is slightly shifted northward and anomalous northwesterly wind prevails over Northeast and Southwest China (Fig. 7d), reducing precipitation over Southwest, North, and Northeast China (Fig. 11d). As mentioned before, asymmetric features of CP-ENSO over the equatorial region are similar to those of CP-La Niña but are not significant (Fig. 7f). However, asymmetric responses of winter precipitation to CP-ENSO are shown as positive anomalies in East China and negative anomalies in North and Northeast China (Fig. 11f), which is closer to those in CP-El Niño. Thus, the impact of the ENSO events on precipitation over China remains complex. Note that the conclusions in this study are qualitatively consistent with those in previous studies (Weng et al., 2007; Feng et al., 2010b; Yuan and Yan, 2013), except for some different responses in South China, which may be related to a different period chosen in this study. Previous studies focused on the period after 1979, while this study focuses on the ENSO events during 1961–2010; therefore, there are more samples used in this study. Moreover, it can also be seen that the relationship between ENSO and East Asian climate is quite complex.

6. Conclusions

Based on monthly mean SST, precipitation reconstruction, outgoing longwave radiation from NOAA, NCEP/NCAR reanalysis, and SODA products during 1961–2010, the spatial distributions of SSTAs and their associated asymmetric features for the EP and CP types of ENSO events were analyzed. Each dynamic process was diagnosed via the heat budget equation, in order to explore possible mechanisms for the asymmetry of SSTAs in the two types of ENSO. Moreover, atmospheric responses to the asymmetry for the two types of ENSO events were examined. The conclusions are as follows:

1. The SSTAs of the two types of ENSO exhibit asymmetric features in space and time and in intensity. The EP-El Niño (CP-La Niña) shows a stronger asymmetry of intensity than EP-La Niña (CP-El Niño) in an EP-ENSO (CP-ENSO) event. In terms of temporal asymmetric features, the EP-El Niño (CP-La Niña) is characterized by a longer duration than EP-La Niña (CP-El Niño). The cold anomalies in the CP-La Niña event even last to the following autumn.

2. The two types of El Niño events are primarily maintained by two feedback mechanisms in the development and decay stages. Generally, the thermocline feedback plays a dominant role in EP-El Niño, while the zonal advection feedback is more important in CP-El Niño. The dynamic mechanisms are more complex in the two types of La Niña events. EP-La Niña develops slowly but decays fast, which is crucially affected by the zonal advection feedback during its evolution. However, vertical advection is slightly stronger in the development stage of CP-La Niña, while both vertical and zonal advectons are fairly important in the decay stage. Although the dominant mechanisms vary in the development and decay stages for the two types of events, oceanic vertical advection plays a key role in the asymmetry of anomalous SST.

3. Due to asymmetries in space and amplitude between cold and warm events for the two types of ENSO, both local atmospheric responses directly forced by SSTAs and remote responses forced via teleconnection show strong asymmetry, which is consistent with the asymmetric distribution of SSTAs, that is, the asymmetric distributions of atmospheric responses in EP-ENSO (CP-ENSO) are similar to those associated with EP-El Niño (CP-La Niña). What is more, the intensity of EP-ENSO-related asymmetric responses is much stronger than that of CP-ENSO-related asymmetric responses.

Asymmetric features for the two types of ENSO were compared in this study. The results showed that the asymmetric distributions of SSTAs for the two types of ENSO led to asymmetric atmospheric responses, bringing out different climatic impacts over neighboring countries and Pacific. However, global climatic impacts caused by asymmetry for the two types
of ENSO events have not been fully investigated. Considering that the two types of ENSO events are reacted as symmetric systems in forecast models, we need to study the asymmetric features for the two types of ENSO to improve the prediction of ENSO. As a result, more studies are required to understand the climatic impacts of the asymmetry for the two types of ENSO events.

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