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Interdecadal changes in the asymmetric impacts of ENSO on wintertime rainfall over China and atmospheric circulations over western North Pacific

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Abstract

Based on data diagnoses, in this study the interdecadal changes in asymmetric impacts of ENSO on wintertime East Asian climate are investigated. It is found that the Pacific Decadal Oscillation (PDO) can significantly modulate the asymmetry in the responses of the East Asian climate to El Niño and La Niña events. In positive PDO phase the response is asymmetric with a strong anomalous anticyclone over western North Pacific (WNP) and significant positive rainfall anomalies over southern China during El Niño winters, but a weak anomalous cyclone over WNP and insignificant negative rainfall anomalies over southern China during La Niña winters. However, such asymmetric responses do not appear in negative PDO phase, with comparable amplitudes of anomalous circulations over WNP and rainfall over southern China in El Niño and La Niña winters. Further analyses reveal that the warm background of the tropical Pacific in positive PDO phase causes significant difference in the amplitudes of convection anomalies over tropical western Pacific, resulting in asymmetric responses of the WNP circulation and rainfall over southern China to El Niño and La Niña events. Nevertheless, the cold background in negative PDO phase reduces the amplitude difference between El Niño and La Niña winters. A comparable convection anomalies appear in tropical western Pacific in El Niño and La Niña winters and the asymmetric responses do not occur.

Keywords Pacific Decadal Oscillation · El Niño–Southern Oscillation · East Asian wintertime climate

1 Introduction

The El Niño–Southern Oscillation (ENSO) is the strongest signal in the interannual climate variability, which can exert a significant influence on the global climate. Many studies have shown that the ENSO cycle has strong relationship with the East Asian winter monsoon (EAWM) and is an important factor affecting the monsoon circulation and rainfall in China (Li 1990; Zhang et al. 1996, 2017; Tomita and Yasunari 1996; Tao and Zhang 1998; Chen et al. 2000; Chen 2002; Huang et al. 2004; Wang and Feng 2011). The EAWM exhibits opposite characteristics during the cold and warm phases of ENSO, with a weak EAWM during El Niño and a strong one during La Niña (Li 1990; Ni et al. 1995; Zhang et al. 1996; Chen 2002). However, it has been demonstrated that the relationship between the EAWM and ENSO is asymmetric. The impact of La Niña on the EAWM is much weaker than that of El Niño (Ni et al. 1995; Zhang et al. 1996; Chen 2002). Meanwhile, the effect of ENSO on wintertime rainfall in China is also asymmetric. Although positive and negative rainfall anomalies occur in winter over

This paper is a contribution to the special collection on ENSO Diversity. The special collection aims at improving understanding of the origin, evolution, and impacts of ENSO events that differ in amplitude and spatial patterns, in both observational and modeling contexts, and in the current as well as future climate scenarios. This special collection is coordinated by Antonietta Capotondi, Eric Guilyardi, Ben Kirtman and Sang-Wook Yeh.

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southern China during El Niño and La Niña events, respectively, the positive anomalies are strong and statistically significant (Zhang et al. 1999; Zhang and Sumi 2002), while the negative anomalies are weak and non-significant (Zhang et al. 2015; Li et al. 2015).

The influences of El Niño and La Niña on the East Asian climate are through the anomalous anticyclone and cyclone over western North Pacific (WNP) in the lower troposphere, respectively (Zhang et al. 1996, 2015, 2017; Wang et al. 2000; Wu et al. 2010; Li et al. 2017). It has been shown that the anomalous anticyclone in an El Niño winter is much stronger than the anomalous cyclone in a La Niña winter (Wu et al. 2010; Zhang et al. 2015; Li et al. 2015). As a result, the East Asian climate in winter is more strongly affected by El Niño than by La Niña. The asymmetric responses of East Asian climate to El Niño and La Niña are attributed to the difference in the intensities of the anomalous anticyclone and cyclone over WNP, which are determined by the difference in the forcing over tropical western Pacific related to El Niño and La Niña (Wu et al. 2010; Zhang et al. 2015; Li et al. 2015).

Previous studies have revealed that the interannual relationship between the EAWM and ENSO has significant interdecadal variation (Zhou et al. 2007; Wang et al. 2008; Ding et al. 2010; Chen et al. 2013; Yuan et al. 2014; Xue et al. 2018). The Pacific Decadal Oscillation (PDO), the most significant interdecadal signal in the North Pacific (Mantua et al. 1997), is the key factor regulating the interannual relationship between ENSO and the East Asian monsoon (Chen et al. 2013). Wang et al. (2008) claimed that the relationship between ENSO and EAWM is not significant in positive PDO phase, while ENSO has a notable influence on the EAWM in negative PDO phase.

As mentioned above, the impacts of El Niño and La Niña on the East Asian winter climate are significantly asymmetric. However, there exist interdecadal changes in the relationship between ENSO and EAWM. Until now it is unknown if there are interdecadal changes in the asymmetric impacts of El Niño and La Niña on the East Asian winter climate and how the asymmetric impacts are affected by PDO. Therefore, in this study we will investigate the interdecadal changes in the asymmetric impacts of El Niño and La Niña on the wintertime rainfall over China and circulations over East Asia, especially the role played by PDO. In fact, as reviewed by Wang and Lu (2017), almost all the studies about the modulations of PDO on the East Asian winter climate only considered the surface air temperature. Therefore, it is also meaningful to investigate how the situation is for rainfall.

The remaining of this paper is organized as follows. The data and methods are described in Sect. 2. In Sect. 3, the asymmetric features for the anomalous circulation over WNP and rainfall over southern China associated with ENSO in different PDO phases are investigated. Section 4 explores the physical reasons for the effect of PDO on the asymmetry in the relationship between East Asian winter climate and ENSO in terms of sea surface temperature (SST) in tropical Pacific and convections over tropical western Pacific in different PDO phases. Conclusions and discussions are given in Sect. 5.

2 Data and methods

The datasets used in this paper include: (1) the monthly rainfall data from 160 meteorological stations from the China Meteorological Administration; (2) the monthly horizontal winds, specific humidity as well as sea level pressure (SLP), at a resolution of $2.5° \times 2.5°$ derived from the reanalysis data of the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) (Kalnay et al. 1996); and (3) the monthly sea surface temperature (SST) with a resolution of $1° \times 1°$ obtained from the Met Office Hadley Center (Rayner et al. 2003).

All of the data used in this study cover the period from 1951 to 2010. The anomaly for each variable is defined as the departure from the climatological mean during 1951–2010. Because the anomalous rainfall associated with ENSO mainly occurs in southern China (Zhang et al. 1999, 2015; Zhang and Sumi 2002), the rainfall stations located in south part of China (18°–41°N, 90°–125°E) are used in this work. Ultimately, as shown in Fig. 1, a total of 124 stations with no missing data are chosen from this area. The winter is defined as the half year in the period from November to the April of next year. For example, the winter half year in 1951 refers to the period from November 1951 to April 1952.

The SST anomalies (SSTAs) averaged over the NINO3 region (150°–90°W, 5°S–5°N) is taken as an index for an El Niño or La Niña. The El Niño (La Niña) episode is defined

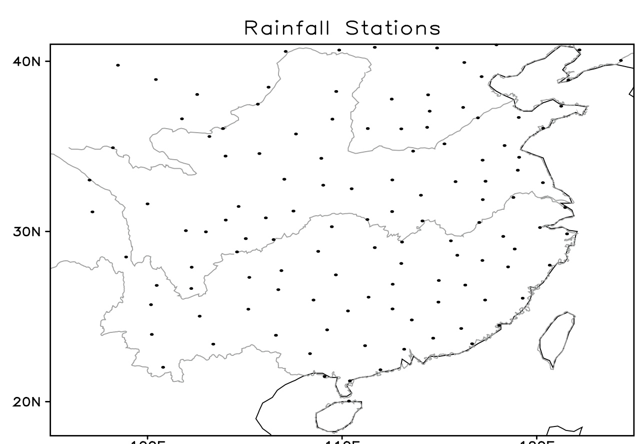

Fig. 1 Distribution of 124 rainfall observational stations (dots)

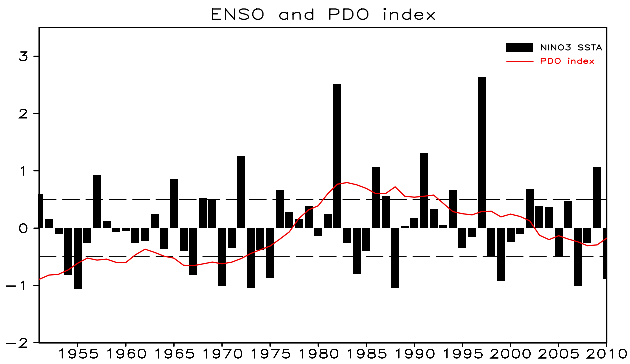

Fig. 2 Time series of the 11-year running mean of PDO index (red line; units: °C) and ENSO index (bars; units: °C) in winter half years during 1951–2010

when the NINO3 SSTAs in the winter half year are greater (less) than 0.5 °C (−0.5 °C). The PDO index provided by Mantua is obtained from the website http://research.jisao.washington.edu/pdo/, which covers the period from 1900 to 2016. To obtain the interdecadal component of PDO, an 11-year running mean is applied to the PDO index and the interdecadal index in 1951–2010 is chosen in this study. The time series of the PDO and ENSO indices in winter half years from 1951 to 2010 are shown in Fig. 2. As seen in Fig. 2, positive PDO phase were in the period from 1978 to 2002, and negative phase from 1951 to 1977 and from 2003 to 2010. According to the criteria above, there were seven El Niño and four La Niña winters in positive PDO phase, while seven El Niño and nine La Niña winters in negative PDO phase, which are listed in Table 1. In this study, the two-sided student *t* test is used for checking the statistical significance.

3 Anomalous rainfall over southern China and circulation over WNP

3.1 Rainfall anomalies over southern China

Figure 3 shows composites of rainfall anomalies in El Niño and La Niña winter half years over southern China in different PDO phases. In positive PDO phase, significant positive rainfall anomalies appear over southern China in El Niño

Table 1 Classification of ENSO based on PDO phases in winter half years

PDO phases	Positive phase (1978–2002)	Negative phase (1951–1977; 2003–2010)
El Niño	1982; 1986; 1987; 1991; 1994; 1997; 2002	1951; 1957; 1965; 1968; 1972; 1976 2009
La Niña	1984; 1988; 1998; 1999	1954; 1955; 1967; 1970; 1973; 1975 2005; 2007; 2010

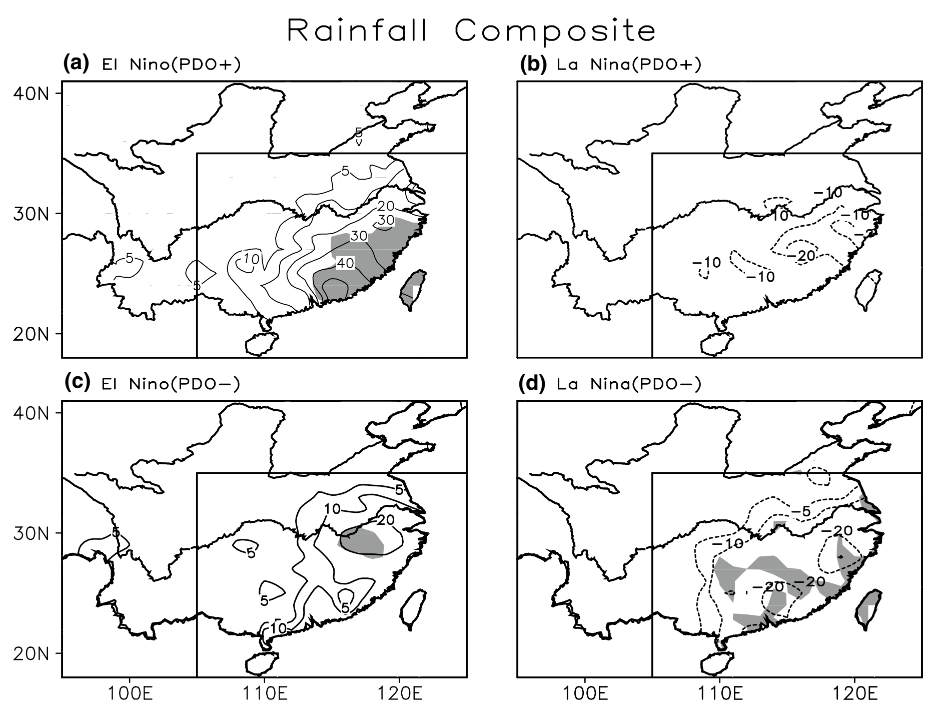

Fig. 3 Composites of rainfall anomalies over southern China in PDO positive phase for **a** El Niño and **b** La Niña winter half years, and in PDO negative phase for **c** El Niño and **d** La Niña winter half years (units: mm/month). Shadings indicate areas with statistical significance exceeding the 95% confidence level. Rectangular region presents southern China (south of 35°N and east of 105°E)

winter half years (Fig. 3a), with a maximum over 50 mm/month around the coastal area of southern China, and most areas to the south of the Yangtze River exceeding the 95% significance level. During La Niña winters (Fig. 3b), however, negative rainfall anomalies appearing over southern China are much weaker, with a maximum center of only − 20 mm/month located in the provinces of Fujian and Zhejiang (25°–30°N, 113°–120°E). The result of a *t*-test shows that the negative anomalies do not exceed the 95% significance level. Therefore, in the positive phase of PDO, the response of rainfall anomalies over southern China to ENSO is significantly asymmetric, i.e. statistically significant positive rainfall anomalies in El Niño winters but no statistically significant negative anomalies in La Niña winters, which are consistent with the results of Zhang et al. (2015).

In negative PDO phase, although positive rainfall anomalies are apparent over southern China in El Niño winter half years (Fig. 3c), the amount of maximum rainfall anomalies is only about 1/3 of that observed in positive PDO phase, and only a small area around the lower reaches of Yangtze River exceeds the 95% significance level. During La Niña winters (Fig. 3d), the area and intensity of negative rainfall anomalies over southern China increase obviously. The geographical range of less than − 10 mm rainfall anomalies almost reaches the scope that positive anomalies occur during El Niño winters in positive PDO phase (Fig. 3a). The result of a *t* test shows that the region exceeding the 95% level of statistical significance is larger than that during La Niña events in positive PDO phase (Fig. 3b). The intensities of rainfall anomalies are comparable during El Niño and La Niña winters. From Fig. 3 it can be clearly seen that the asymmetry for the responses of wintertime rainfall anomalies over southern China to El Niño and La Niña are different in positive and negative PDO phases. The asymmetry exists only in positive PDO phase but not in negative PDO phase.

Figure 4 shows the rainfall anomalies averaged over southern China (south of 35°N and east of 105°E, rectangular region in Fig. 3) in El Niño and La Niña winter half years during the two PDO phases. It is shown that the responses of wintertime rainfall over southern China to ENSO are significantly modulated by PDO. The amount of the rainfall anomalies in positive PDO phase are 12.30 mm/month and − 3.17 mm/month in El Niño and La Niña winters, respectively. The absolute value of the former is significantly larger than that of the later, by about four times, indicating asymmetric rainfall anomalies during El Niño and La Niña winters. However, during negative PDO phase, the amount of rainfall anomalies in El Niño winters decreases and that in La Niña winters increases compared to those in positive PDO phase. The absolute amounts of rainfall anomalies in El Niño and La Niña winters are nearly the same, at 6.99 mm/month and − 8.46 mm/month, in El Niño and La Niña winters, respectively. Hence, the responses of rainfall

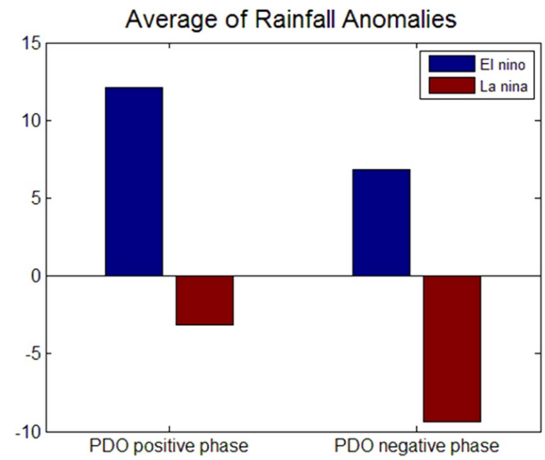

Fig. 4 Rainfall anomalies averaged over southern China (south of 35°N and east of 105°E, the rectangular region in Fig. 3) for El Niño (blue bars) and La Niña (red bars) winter half years in positive (left two bars) and negative (right two bars) PDO phases

over southern China to ENSO in negative PDO phase do not exhibit an asymmetry as shown in positive PDO phase.

To further demonstrate the effect of PDO in the rainfall anomalies associated with ENSO, in Fig. 5 we show the differences in composites of rainfall anomalies between positive and negative PDO phases in El Niño and La Niña winter half years, respectively. In both El Niño and La Niña winters, positive differences appear over southern China and are statistically significant exceeding the 95% significance level around the southern coast. It is illustrated that the positive rainfall anomalies in positive PDO phase are significantly larger than those in negative PDO phase (Fig. 5a). Similarly, in La Niña winters, the negative rainfall anomalies in positive PDO phase are significantly smaller than those in negative PDO phase (Fig. 5b). These differences indicate that the PDO has significant influence on the rainfall anomalies associated with ENSO.

3.2 Circulation and moisture transport anomalies

Many studies have demonstrated that the effects of El Niño and La Niña on the East Asian winter climate are through an anomalous anticyclone and cyclone in the lower troposphere over WNP, respectively (Zhang et al. 2015, 2017; Li et al. 2017). Therefore, the anomalous 850-hPa circulations over WNP in El Niño and La Niña winter half years in different PDO phases are analyzed in this section.

As shown in Fig. 6, an obvious anomalous anticyclone appears over WNP during El Niño winters in both positive (Fig. 6a) and negative (Fig. 6c) phases of PDO. The anomalous southwesterly winds on the northwest side of the anomalous anticyclone directly affect southeastern China, forming an obvious water vapor channel and leading to more

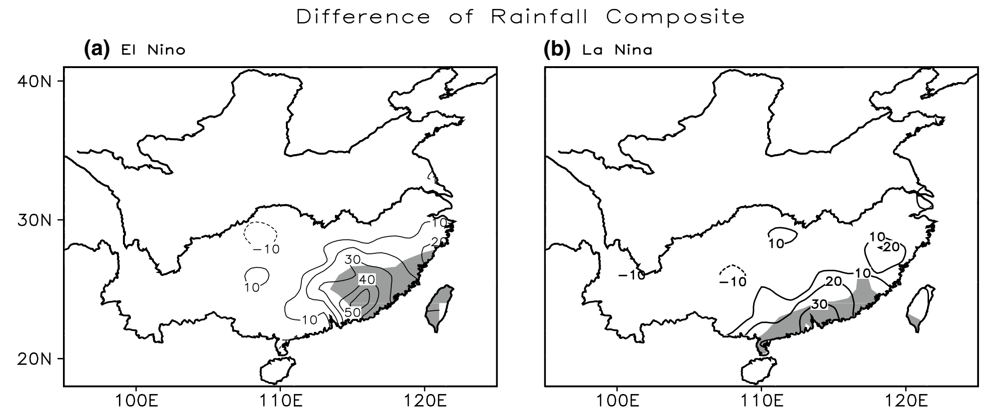

Fig. 5 Difference in composites of rainfall anomalies between positive and negative PDO phases in **a** El Niño and **b** La Niña winter half years (units: mm/month). Shadings are the areas with statistical significance exceeding the 95% confidence level

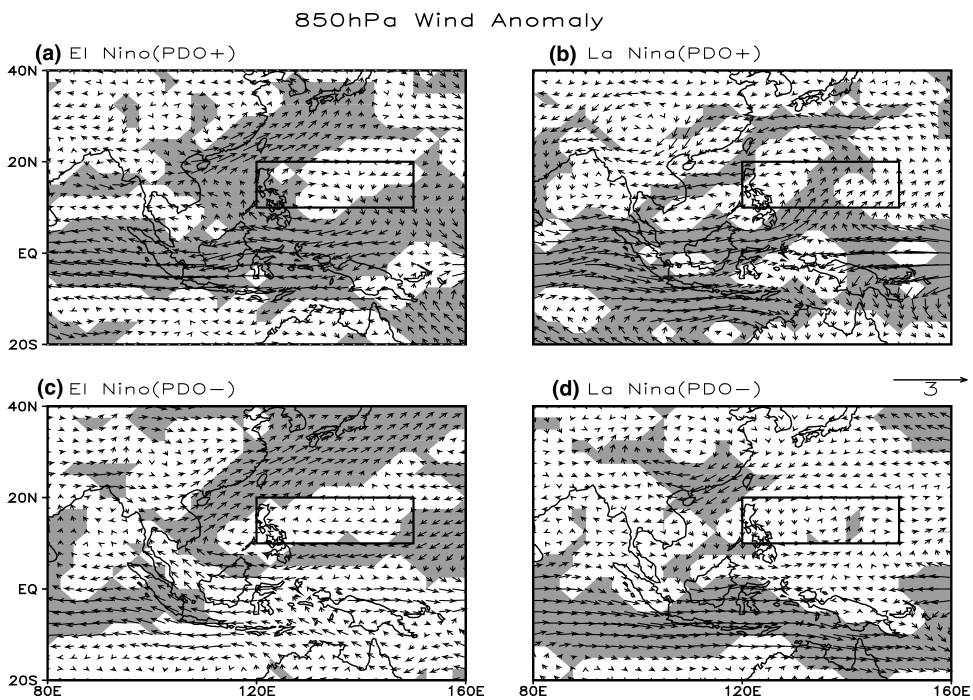

Fig. 6 Composites of 850-hPa wind anomalies in positive PDO phase for **a** El Niño and **b** La Niña winter half years, and in negative PDO phase for **c** El Niño and **d** La Niña winter half years (units: m/s). Shadings indicate areas with statistical significance exceeding the 95% confidence level. The rectangular region presents the Philippine Sea (10°–20°N, 120°–150°E)

rainfall over southern China (Zhang and Sumi 2002; Li et al. 2015). In La Niña winter half years, the anomalous cyclone appears over WNP during both PDO phases (Fig. 6b, d). The anomalous northeasterly winds associated with the anomalous cyclone over WNP control most of the regions of southern China, hindering the transport of water vapor from the south and causing a reduction in rainfall (Zhang et al. 2015; Li et al. 2015).

The anomalies of water vapor flux and its divergence in positive and negative PDO phases for El Niño and La Niña winters are shown in Fig. 7. In association with the anomalous anticyclone over WNP, in El Niño winters the anomalies of northeastward moisture transport and convergence over southern China are much stronger in positive PDO phase (Fig. 7a) than those in negative PDO phase (Fig. 7c), with the largest anomalous convergence being around -9.0 and -3.0×10^{-7} g/cm^2 hPa s in positive and negative PDO phases, respectively. However, in La Niña winters the anomalies of southwestward moisture transport and divergence over southern China associated with the anomalous cyclone over WNP become much weaker in positive PDO phase (Fig. 7b) than those in negative PDO phase (Fig. 7d), with the largest anomalous divergence being over 3.0 and 6.0×10^{-7} g/cm^2 hPa s in positive and negative PDO phases, respectively. It can be seen that both anomalies of water vapor flux and its divergence over southern China in El Niño and La Niña winters show clearly asymmetric in positive PDO phase, but not in negative PDO phase.

Wang et al. (2000) suggested that the intensity of the anomalous anticyclone over WNP can be measured by using the SLP anomalies averaged over the Philippine Sea (10°–20°N, 120°–150°E). To compare the difference

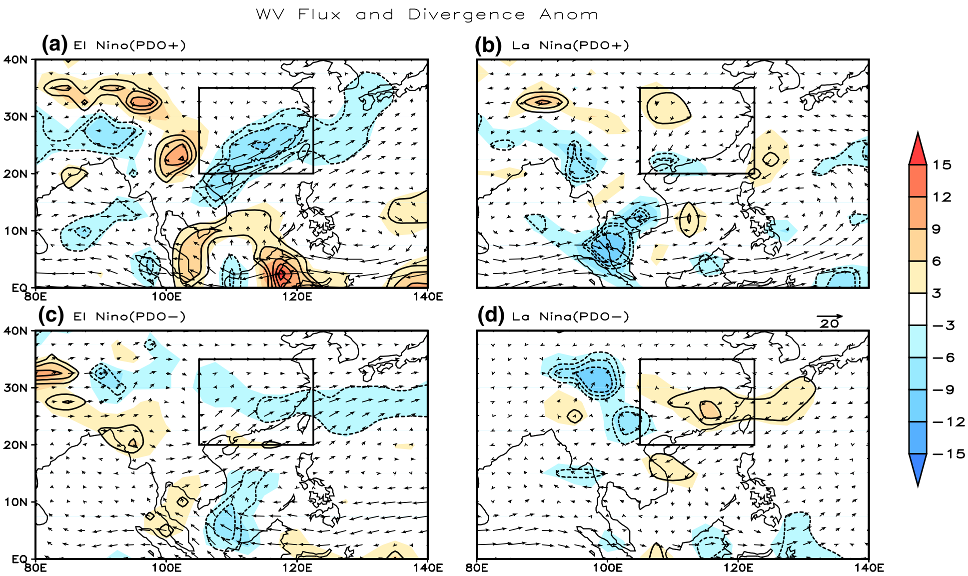

Fig. 7 Anomalies of water vapor flux (vectors; units: g/cm^2 hPa s) and its divergence (shadings; units: 10^{-7} g/cm^2 hPa s) in positive PDO phase for **a** El Niño and **b** La Niña winter half years, and in negative PDO phase for **c** El Niño and **d** La Niña winter half years. Contours are those with statistical significance exceeding the 95% confidence level. Rectangular region presents southern China (20°–35°N, 105°–125°E)

in anomalous circulations between positive and negative PDO phases shown in Fig. 6 and their effects on the water vapor conditions over southern China, the anomalies of SLP averaged over the Philippine Sea (10°–20°N, 120°–150°E, the rectangular region in Fig. 6) and the anomalous water vapor flux (WVF) divergences averaged over southern China (20°–35°N, 105°–125°E, the rectangular region in Fig. 7) are calculated, and the results are given in Fig. 8.

Figure 8 shows that in positive PDO phase the intensities of anomalous circulations over WNP in El Niño and La Niña winters are 1.33 and − 0.84 hPa, respectively (Fig. 8a), and the anomalous WVF divergences over southern China are -1.86×10^{-7} and 0.50×10^{-7} g/cm^2 hPa s, respectively (Fig. 8b). Both the intensities of the anomalous circulation and WVF divergence in El Niño winters are much larger than those in La Niña winters. We also calculated the skewness of anomalous SLP and WVF divergence in El Niño winters, which are 1.30 and − 1.25, respectively, both exceeding 95% significance level. However, the skewness of anomalous SLP and WVF divergence in La Niña winters are − 1.03 and 0.89, which are not statistically significant. Therefore, the significant positive rainfall anomalies appear over southern China in El Niño winter half years (Fig. 3a), but no significant negative rainfall anomalies occur in La Niña winters (Fig. 3b). This indicates that the asymmetric circulation responses to ENSO over WNP are the main reason for asymmetric rainfall anomalies over southern China.

In the negative phase of PDO, the intensities of the anomalous anticyclone over WNP (0.70 hPa) (Fig. 8a) and the anomalous WVF convergence over southern China (-1.04×10^{-7} g/cm^2 hPa s) (Fig. 8b) for El Niño winters are almost comparable to those of the anomalous cyclone over WNP (− 0.87 hPa) (Fig. 8a) and the anomalous WVF divergence over southern China (1.14×10^{-7} g/cm^2 hPa s) (Fig. 8b) for La Niña winters, respectively. The skewness of the anomalous SLP is 1.28 for El Niño winters and − 1.21 for La Niña winters, both being statistically significant. As for the anomalous WVF divergence, the skewness is − 0.38

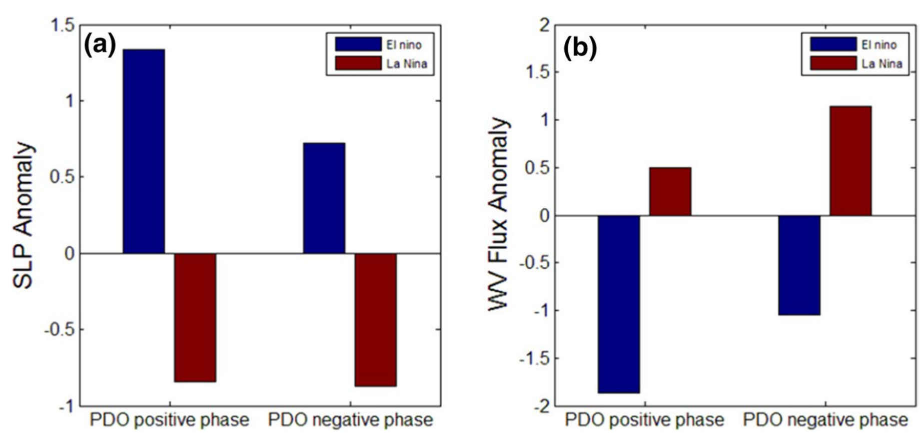

Fig. 8 Anomalies of **a** SLP (units: hPa) averaged over the Philippine Sea (10°–20°N, 120°–150°E, the rectangular region in Fig. 6) and **b** water vapor flux divergence (units: 10^{-7} g/cm^2 hPa s) averaged over southern China (20°–35°N, 105°–125°E, the rectangular region in Fig. 7) during El Niño (blue bars) and La Niña (red bars) winter half years in positive (left two bars) and negative (right two bars) PDO phases

for El Niño winters and 1.16 for La Niña winters, with the former being not statistically significant but the latter becoming statistically significant exceed the 95% level.

Compared with positive PDO phase, the anomalous anticyclone and WVF convergence during El Niño winters weaken from 1.33 hPa and -1.86×10^{-7} g/cm^2 hPa s in positive PDO phase to 0.70 hPa and -1.04×10^{-7} g/cm^2 hPa s in negative PDO phase, respectively, and the WVF divergence in La Niña winters enhances from 0.50×10^{-7} to 1.14×10^{-7} g/cm^2 hPa s. It is obvious that the differences in the intensities of both anomalous circulations and WVF convergence between El Niño and La Niña winters reduce in negative PDO phase. Therefore, the comparable intensities of the anomalous anticyclone and the anomalous cyclone in negative PDO phase lead to comparable intensities of the WVF divergence anomalies over southern China in El Niño and La Niña winters. As a result, the asymmetric responses of rainfall anomalies to ENSO over southern China do not occur in the negative phase of PDO.

4 Mechanism of PDO modulation

The analyses presented in the previous sections show that the asymmetric features of the anomalous circulations over WNP and rainfall over southern China associated with El Niño and La Niña are related to PDO phases. The asymmetric responses of wintertime rainfall anomalies over southern China to El Niño and La Niña in positive PDO phase are affected by the asymmetric circulation anomalies over WNP and associated anomalous WVF convergence over southern China. However, such asymmetric responses do not occur in negative PDO phase. The comparable intensities of the WNP circulation anomalies in El Niño and La Niña result in comparable intensities of anomalous WVF convergence in negative PDO phase, leading to a reduced difference in the intensities of southern China rainfall anomalies in winter. In this section, the possible mechanism for the modulation of PDO on the anomalous circulations over WNP in El Niño and La Niña winters will be discussed.

4.1 SST in tropical Pacific

Previous studies have shown that anomalous atmospheric circulations during ENSO episodes are related to the distribution of SSTAs. The SSTAs in the tropical western Pacific associated with ENSO are the main reason for the appearance of anomalous anticyclones (cyclones) during El Niño (La Niña) winters (Zhang et al. 2015). The SSTAs in the tropical western Pacific as well as their zonal gradient between the central and western equatorial Pacific can affect the convections over there (Zhang et al. 1996; Tokinaga et al. 2012), which stimulate atmospheric Rossby waves through convective cooling (heating) anomalies in El Niño (La Niña) winters and cause the anomalous anticyclone (cyclone) over WNP in the lower troposphere (Zhang et al. 1996, 2015).

Figure 9 presents composites of tropical SSTAs associated with ENSO in the different phases of PDO. In both positive and negative PDO phases, the typical ENSO features over tropical Pacific are shown clearly, with positive (negative) SSTAs in tropical central-eastern Pacific and negative (positive) SSTAs in western tropical Pacific during El Niño (La Niña) winter half years. However, notable differences between the two phases can be observed. Over tropical central-eastern Pacific, positive SSTAs during El Niño winters are much stronger and extend more widely in positive PDO phase (Fig. 9a) than in negative PDO phase (Fig. 9c), while negative SSTAs in La Niña winters are stronger and extend more widely in negative phase of PDO (Fig. 9d) than in positive PDO phase (Fig. 9b). In tropical western Pacific, in El Niño winter half years, the negative PDO phase (Fig. 9c) shows stronger and larger areas of negative SSTAs than the positive PDO phase (Fig. 9a); but in La Niña winters, stronger positive SSTAs are apparent in positive PDO phase (Fig. 9b) compared with the negative phase of PDO (Fig. 9d).

The characteristics of the SSTAs distribution described above indicate a clear modulation of PDO on the distribution of SSTAs associated with ENSO. The mechanism for the PDO's modulation is easily understandable. The positive (negative) PDO phase corresponds to positive (negative) SSTAs over the tropical Pacific in the interdecadal time scale (Mantua et al. 1997). Therefore, during El Niño episodes, in the positive (negative) phase of PDO the interdecadal positive (negative) tropical SSTAs encourage stronger (weaker) positive SSTAs in tropical central-eastern Pacific and weaker (stronger) negative SSTAs in the tropical western Pacific (Fig. 9a, c). In La Niña episodes, the interdecadal positive (negative) SSTAs associated with positive (negative) PDO phase weaken (strengthen) negative SSTAs in the tropical central-eastern Pacific and strengthen (weaken) positive SSTAs in western Pacific (Fig. 9b, d). Therefore, the interdecadal variation of SSTAs associated with PDO can modulate the SSTAs related to ENSO not only in tropical central-eastern Pacific, but also in western tropical Pacific.

The above-mentioned distributions of tropical SSTAs in El Niño and La Niña winters in different PDO phases inevitably affect the zonal gradient of SSTAs. To check the asymmetric features of the zonal gradient, we calculated the difference of SSTAs between the central (140°–160°E, 5°S–5°N) and western (160°–80°W, 5°S–5°N) equatorial Pacific and the results are shown in Fig. 10. From this figure the asymmetric features can be clearly seen. In positive PDO phase, the magnitude of the difference in El Niño winters is obviously larger than that in La Niña winters, with the former being -1.20 °C and latter 0.81 °C. However, in

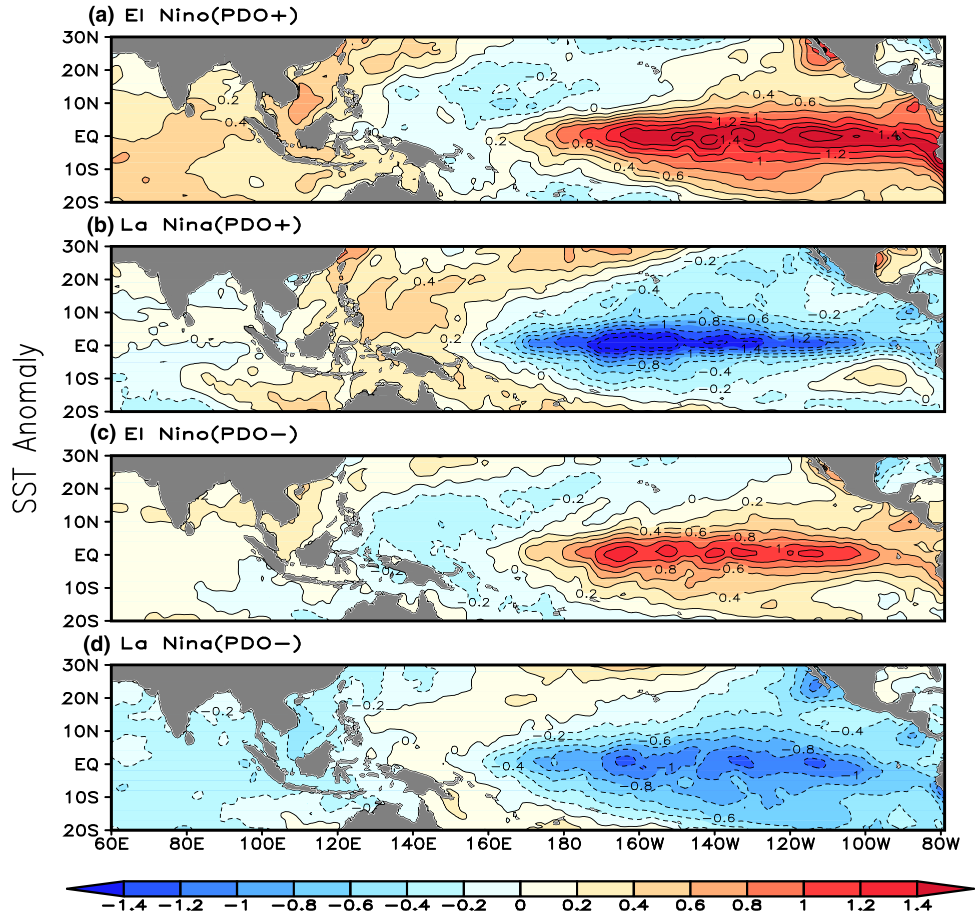

Fig. 9 Composites of SST anomalies in positive PDO phase during **a** El Niño and **b** La Niña winter half years, and in negative PDO phase during **c** El Niño and **d** La Niña winter half years (units: °C)

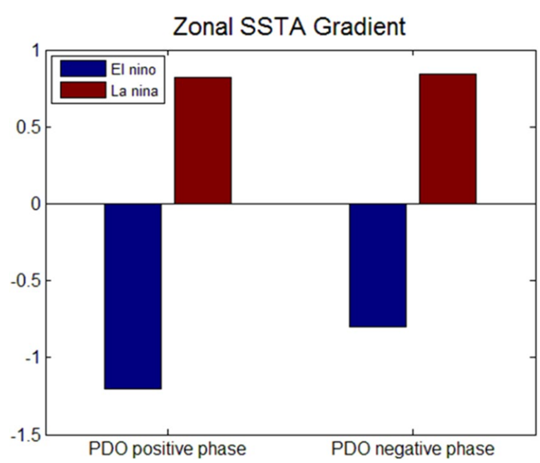

Fig. 10 Difference of SSTAs between the equatorial western Pacific (140°–160°E, 5°S–5°N) and eastern Pacific (160°–80°W, 5°S–5°N) for El Niño (blue bars) and La Niña (red bars) winter half years in positive (left two bars) and negative (right two bars) PDO phases (units: °C)

negative PDO phase the magnitudes in El Niño and La Niña winters are comparable, with the former being −0.82 °C and latter 0.84 °C. It indicates that the zonal gradient of SSTAs between the central and western equatorial Pacific is asymmetric in positive PDO phase but not in negative PDO phase.

The notable differences in the tropical Pacific SSTAs as well as their zonal gradients related to El Niño and La Niña between positive and negative PDO phases can necessarily lead to the imparity of atmospheric heating anomalies associated with ENSO. The impacts of El Niño and La Niña on the atmosphere over tropical western Pacific in winter half years for both PDO phases are analyzed in the next subsection.

4.2 Convection activity

Anomalous heating of ENSO on the atmosphere in tropical regions is closely related to variations in convective activity which releases latent heat to the atmosphere. Zhang et al. (2015) suggested that convection anomalies over tropical western Pacific in association with El Niño and La Niña have notable impacts on atmospheric circulations over WNP during boreal winter. Outgoing longwave radiation (OLR) is often used to measure the intensity of convective activity in the tropics (Morrissey 1986; Zhang et al. 1996). However, since the OLR data are retrieved from satellites, observations of OLR appear only after the mid-1970s and thus cannot be used to examine convections in the whole period of the present study. Previous studies have indicated that the 200-hPa velocity potential and OLR have good coherence when measuring large-scale vertical motion (convection) in the tropics (Janowiak et al. 1998; Chen et al. 2001). Zhang et al. (1996) also demonstrated consistent characteristics of the 200-hPa velocity potential and OLR anomalies during El Niño episodes. Thus, in the present study the 200-hPa velocity potential is used instead of OLR to investigate the convection anomalies associated with El Niño and La Niña for the different phases of PDO. To demonstrate the coherent variations of 200-hPa velocity potential and OLR over tropical western Pacific, we calculated the correlation between them over the region 0°–17.5°N, 110°–140°E for the period of 1979–2010, and the correlation coefficient is as high as 0.88. The high correlation implies that it is reasonable to use the 200-hPa velocity potential to measure the convections over tropical western Pacific.

Figure 11 shows that the east–west distribution of the anomalous 200-hPa velocity potential over tropical Pacific is similar to that of SSTAs shown in Fig. 9, both exhibiting an east–west dipole pattern. Here we can see that positive (negative) SSTAs correspond to negative (positive) 200-hPa velocity potential anomalies and anomalous divergence (converge) of the divergence winds, which are conductive to ascending (descending) motion and a strengthening (weakening) of convections. Zhang et al. (1996, 2015) demonstrated that the impacts of ENSO on the East Asian wintertime climate are through convection anomalies over western tropical Pacific. In an El Niño (La Niña) winter, the atmospheric Rossby wave response to the convective cooling (heating) anomalies over tropical western Pacific lead to an anomalous anticyclone (cyclone) over WNP in the lower troposphere, which influences the East Asian climate.

As shown in Fig. 11, the convection anomalies over tropical western Pacific corresponding to ENSO have obvious differences in different phases of PDO. Anomalous positive 200-hPa velocity potential and convergence of the divergence winds over tropical western Pacific during the positive phase of PDO (Fig. 11a) are significantly stronger than those during the negative phase (Fig. 11c) in El Niño winter half years, resulting in a weakening of anomalous convective cooling over tropical western Pacific and thus an anomalous anticyclone over WNP in negative PDO phase (Fig. 6c). However, in La Niña winters anomalous negative velocity potential and divergence of the divergence winds over tropical western Pacific are weaker during the positive phase of PDO (Fig. 11b) than those during negative PDO phase (Fig. 11d), indicating a strengthening of anomalous convective heating over tropical western Pacific and cyclone over WNP in negative PDO phase (Fig. 6d). Here we can see that in negative PDO phase the difference of the intensities of anomalous anticyclone in El Niño winters and cyclone in La Niña winters become smaller, and, therefore, the asymmetric impacts of El Niño and La Niña on the circulations over WNP do not exist in negative PDO phase.

To further confirm the contrast of the convection anomalies over western tropical Pacific between El Niño and La Niña winters in different PDO phases, we calculated the absolute value of the 200-hPa velocity potential averaged over the tropical western Pacific (0°–17.5°N, 110°–140°E). The differences of the absolute value between El Niño and La Niña are 2.88×10^6 and 0.79×10^6 m^2/s for positive and negative phases of PDO, respectively, with the former being notably larger than the latter. Such differences indicate strong asymmetric forcings of El Niño and La Niña over tropical western Pacific in positive PDO phase but not in negative PDO phase.

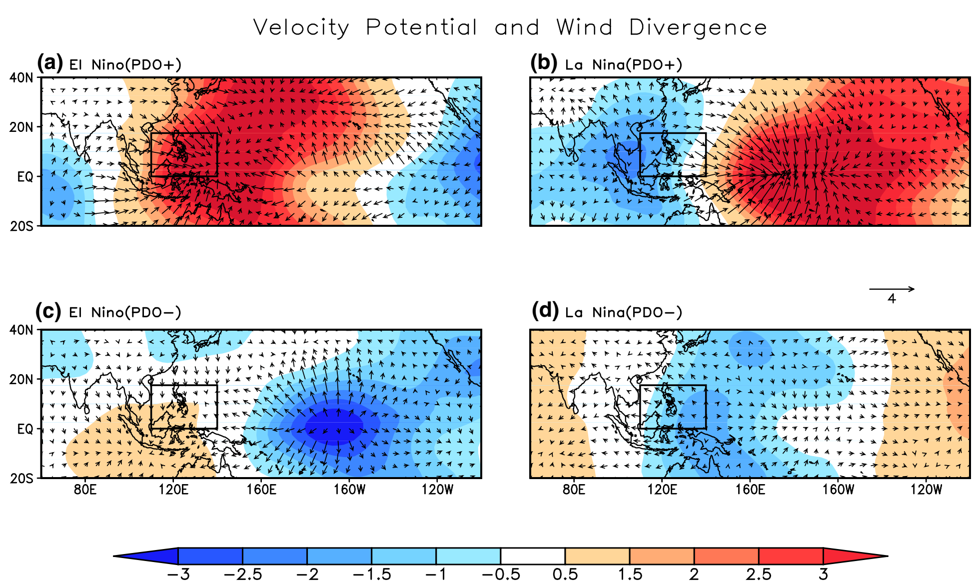

Fig. 11 Composites of anomalous 200-hPa velocity potential (shadings; units: 10^6 m/s) and divergence winds (vectors; units: m/s) in positive PDO phase during **a** El Niño and **b** La Niña winter half years, and in negative PDO phase during **c** El Niño and **d** La Niña winter half years. The rectangular region is for the tropical western Pacific (0°–17.5°N, 110°–140°E)

In Fig. 12, we show the anomalous divergence of divergence winds averaged over tropical western Pacific (0°–17.5°N, 110°–140°E, the rectangular region in Fig. 11) for El Niño and La Niña winter half years in positive and negative PDO phases. In positive PDO phase, the amplitude of anomalous convergence of divergence winds in El Niño winters (-9.61×10^{-7} m/s^2) is much stronger than that of the anomalous divergence in La Niña winters (1.17×10^{-7} m/s^2), and the difference of their absolute values is statistically significant exceeding the 95% significance level. However, in negative PDO phase the difference between the absolute values of the anomalous convergence of divergence winds in El Niño winters (-2.10×10^{-7} m/s^2) and the anomalous divergence in La Niña winters (4.40×10^{-7} m/s^2) becomes much smaller and is not statistically significant. Therefore, in positive PDO phase the significant difference in the magnitudes of anomalous 200-hPa velocity potential and divergence winds between El Niño and La Niña winter half years leads to the asymmetric response of circulation anomalies over WNP. Nevertheless, in negative PDO phase the much smaller difference should be responsible for the non-existing of the asymmetric features.

The modulation of PDO on ENSO as well as associated circulations and convections is physically understandable. The Walker circulation can be affected by both SSTAs and their zonal gradient anomalies between central and eastern equatorial Pacific (Tokinaga et al. 2012). In the positive phase of PDO, the warm tropical Pacific SST related with PDO is superimposed on the positive El Niño SSTAs in central-eastern tropical Pacific and the negative zonal gradient of equatorial SSTAs is larger (Fig. 10). The anti-Walker circulation anomaly associated with El Niño becomes stronger, resulting in stronger anomalous subsidence over tropical western Pacific (Fig. 11a). However, negative SSTAs during La Niña are weakened because of the warmer SST in the positive phase of PDO in central-eastern tropical Pacific, and the positive zonal gradient of equatorial SSTAs is weaker (Fig. 10), which weaken the Walker circulation related with La Niña and anomalous ascent in tropical western Pacific (Fig. 11b). Therefore, during the positive phase of PDO, over tropical western Pacific the weakened convection during El Niño becomes more weakened (Fig. 11a) and strengthened convection during La Niña is also weakened (Fig. 11b), leading to the significant asymmetry of convective heating anomalies over tropical western Pacific between El Niño and La Niña winter half years.

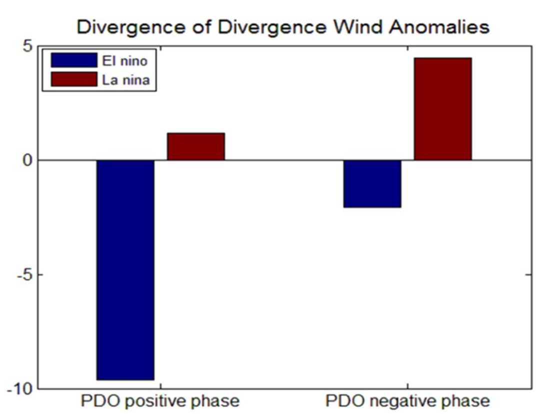

Fig. 12 Anomalous divergence of divergence winds (units: 10^{-7} m/s^2) averaged over the tropical western Pacific (0°–17.5°N, 110°–140°E, the rectangular region in Fig. 11) for El Niño (blue bars) and La Niña (red bars) winter half years in positive (left two bars) and negative (right two bars) PDO phases

In the negative phase of PDO, cold tropical Pacific SST associated with PDO is superimposed on the positive El Niño SSTAs in central-eastern tropical Pacific, leading to a weakening of the anti-Walker circulation anomaly, as well as reduced subsidence anomalies over western tropical Pacific (Fig. 11c). However, the negative SSTAs in central-eastern tropical Pacific during La Niña are strengthened due to the cold SST in the tropical Pacific during negative PDO phase, the anomalous Walker circulation and ascent in tropical western Pacific are enhanced (Fig. 11d). In fact, the comparable magnitudes of the zonal gradient of SSTAs in El Niño and La Niña winters (Fig. 10) also reduce the difference in magnitudes of convection over tropical western Pacific through affecting the Walker circulation. Thus, in negative PDO phase, the difference between the amplitudes of convection anomalies during El Niño and La Niña decreases over the tropical western Pacific compared to the positive PDO phase, leading to the non-significant asymmetry of convective heating anomalies over tropical western Pacific between El Niño and La Niña winter half years.

The above analyses show that, during positive PDO phase, the amplitude of suppressed convection over tropical western Pacific in El Niño become much larger and that of enhanced convection in La Niña much weaker, which causes the asymmetric convective heating anomalies. This should be the main physical reason for the asymmetric circulations over WNP, with a stronger anomalous anticyclone during El Niño and a weaker anomalous cyclone during La Niña (Figs. 6, 8). However, during negative PDO phase, the difference between the amplitudes of weakened convection during El Niño and the enhanced convection during La Niña decrease over tropical western Pacific, which reduce the asymmetry of the convection heating anomalies and atmospheric circulations over WNP.

It can be seen here that the convective activities over tropical western Pacific associated with ENSO are clearly modulated by PDO. The asymmetric atmospheric circulation anomalies over WNP during the positive phase of PDO further lead to the asymmetric WVF divergence and rainfall anomalies over southern China. However, in the negative phase of PDO the asymmetry of anomalous atmospheric circulations over WNP is weakened and results in the absence of asymmetry in WVF divergence and rainfall anomalies.

5 Conclusions and discussions

This study investigated the asymmetric responses of the wintertime anomalous atmospheric circulations over WNP and rainfall over southern China to ENSO in different PDO phases through data diagnoses. The results show that the impacts of El Niño and La Niña on the atmospheric circulations over WNP and rainfall over southern China are asymmetric in the positive phase of PDO but not in negative PDO phase. In positive PDO phase, a strong anomalous anticyclone appears over WNP in lower troposphere during El Niño winters but a weak anomalous cyclone during La Niña winters. The positive and negative rainfall anomalies appear over southern China in El Niño and La Niña winters, respectively, with the former being much stronger and statistically significant while the later much weak and insignificant. The strong anomalous anticyclone enhances the water vapor transport to the north and the anomalous water vapor flux converges significantly over southern China, while the weak anomalous cyclone does not reduces the water vapor transport significantly and weak anomalous divergence of water vapor flux appears over southern China, resulting in significant rainfall anomalies over southern China in El Niño winters but not in La Niña winters.

During the negative phase of PDO, the strength of the anomalous anticyclone over WNP associated with El Niño reduces and that of the anomalous cyclone with La Niña increases, compared to the positive PDO phase. The difference between the amplitudes of the anomalous anticyclone and cyclone declines and their intensities become comparable. Therefore there are no obvious asymmetries in atmospheric circulation anomalies over WNP and rainfall anomalies over southern China in El Niño and La Niña winters in negative PDO phase.

The PDO, as the interdecadal background of SSTAs in tropical Pacific, modulates the asymmetric impacts of ENSO on the atmospheric circulations over WNP. The positive PDO phase corresponds to a warm SST in central-eastern tropical Pacific, which enhances and attenuates El Niño and La Niña events, respectively. The enhanced El Niño and zonal gradient of SSTAs between central and eastern equatorial Pacific leads to stronger anomalous anti-Walker circulation and descending motion over tropical western Pacific associated with El Niño. The intensified descending motion causes stronger convective cooling anomalies over tropical western Pacific, which enhances the atmospheric Rossby wave responses and result in a stronger anomalous anticyclone over WNP. In contrast, the weakened La Niña and zonal gradient of SSTAs between central and eastern equatorial Pacific is associated with a weaker anomalous Walker circulation and ascending motion over tropical western Pacific. The weaker convective heating forms weaker atmospheric Rossby wave responses and anomalous cyclone over WNP. Therefore, in positive PDO phase the enlarged difference in amplitudes of anomalous convective cooling in El Niño and convective heating in La Niña over tropical western Pacific can lead to the asymmetric responses of atmospheric circulations over WNP and thus rainfall in southern China.

The negative phase of PDO provides the cold SST interdecadal background in central-eastern tropical Pacific, which attenuates El Niño and enhances La Niña. The weaker anomalous anti-Walker circulation and stronger Walker circulation are accompanied by a weakened El Niño and enhanced La Niña, respectively, and magnitudes of the zonal gradient of SSTAs in El Niño and La Niña winters are comparable. Compared with positive PDO phase, the descending motion anomalies over tropical western Pacific related to El Niño is weakened, and ascending motion anomalies related to La Niña is strengthened, which narrow the difference in strengths between the convective cooling anomalies in El Niño and heating anomalies in La Niña. As a result, the intensities of the anomalous anticyclone over WNP and positive rainfall anomalies over southern China responded to the reduced convective cooling anomalies over tropical western Pacific in El Niño are comparable to those of the anomalous cyclone and negative rainfall anomalies responded to the enhanced convective heating anomalies in La Niña. Thus, the responses of atmospheric circulations over WNP and rainfall over southern China to El Niño and La Niña during the negative phase of PDO do not appear to be asymmetric.

In this study, the El Niño (La Niña) episode is defined as the NINO3 SSTAs greater (less) than 0.5 °C (−0.5 °C) in the winter half year. In fact, the eastern Pacific (EP) and central Pacific (CP) ENSO may have different impacts on the East Asian wintertime climate (e.g. Weng et al. 2009; Su et al. 2013; Feng et al. 2017). The results of our present study should be regarded as the impacts of the EP ENSO in the whole winter half year. The asymmetric impacts of the CP ENSO on the East Asian wintertime climate as well as their interdecadal changes are worth for future investigation.

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