Decadal Anomalies of Winter Precipitation over Southern China in Association with El Niño and La Niña

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ABSTRACT

Using multiple datasets, this paper analyzes the characteristics of winter precipitation over southern China and its association with warm and cold phases of El Niño–Southern Oscillation during 1948–2011. The study proves that El Niño is an important external forcing factor resulting in above-normal winter precipitation in southern China. The study also reveals that the impact of La Niña on the winter precipitation in southern China has a decadal variability.

During the winter of La Niña before 1980, the East Asian winter monsoon is stronger than normal with a deeper trough over East Asia, and the western Pacific subtropical high weakens with its high ridge retreating more eastward. Therefore, anomalous northerly winds dominate over southern China, leading to a cold and dry winter. During La Niña winter after 1980, however, the East Asian trough is weaker than normal, unfavorable for the southward invasion of the winter monsoon. The India-Burma trough is intensified, and the anomalous low-level cyclone excited by La Niña is located to the west of the Philippines. Therefore, anomalous easterly winds prevail over southern China, which increases moisture flux from the tropical oceans to southern China. Meanwhile, La Niña after 1980 may lead to an enhanced and more northward subtropical westerly jet over East Asia in winter. Since southern China is rightly located on the right side of the jet entrance region, anomalous ascending motion dominates there through the secondary vertical circulation, favoring more winter precipitation in southern China. Therefore, a cold and wet winter, sometimes with snowy and icy weathers, would occur in southern China during La Niña winter after 1980. Further analyses indicate that the change in the spatial distribution of sea surface temperature anomaly during the La Niña mature phase, as well as the decadal variation of the Northern Hemisphere atmospheric circulation, would be the important reasons for the decadal variability of the La Niña impact on the atmospheric circulation in East Asia and winter precipitation over southern China after 1980.

Key words: East Asian winter monsoon, winter precipitation, El Niño and La Niña, asymmetry, decadal variability

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1. Introduction

As one of the most active components in the global climate system, the East Asian winter monsoon (EAWM) is an important climate feature over East Asia in boreal winter, and one of the most important factors influencing the winter climate in China. EAWM often brings about various kinds of hazards, such as cold surge, low temperature, snow and ice weather, etc. (Ding, 1990; Chen et al., 1991; Huang et al., 2008). Most previous studies have focused on the temperature variations in winter and the associated physical mechanisms (Tao, 1957; Li, 1989; Ding, 1990; Wu et al., 1999). Few studies have concerned

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about the winter precipitation anomaly features, probably because the regions controlled by the winter monsoon are often cold and dry, and winter precipitation accounts for only a small proportion of the annual precipitation (Chen et al., 2008). On the other hand, winter precipitation anomaly may not cause huge floods like the East Asian summer monsoon precipitation does. However, winter precipitation shows an interannual and interdecadal variability over different regions in China (Xu et al., 1999; Xu and Chan, 2002). Excessively more winter precipitation, in the form of snow or freezing rain, not only brings inconvenience to people's travel, but also causes threat to people's life and property. During some other years, excessively less winter precipitation may also induce low soil moisture and drought, and seriously affect the crop production. For example, during mid January and early February 2008, an unprecedented disaster of low temperature, persistent rain, snow and ice storms occurred in the Yangtze River basin and South China, which killed at least 120 people and caused direct economic losses of over 150 billion yuan (Li et al., 2008; Wang Zunya et al., 2008; Wen et al., 2009). However, during late 2008 and early 2009, the severe drought in northern China affected 10 million hectares of crops, and resulted in 4 million people short of drinking water. The direct economic losses were as high as 1.6 billion yuan in only Anhui Province (Gao and Yang, 2009). Therefore, with the social and economic development, the impact of winter climate on the agriculture, energy, and water balance in China is becoming more and more important. Forecasting of the winter precipitation anomaly has also become an essential work in the meteorological operation (He et al., 2006).

On the interannual timescale, the major mode of winter precipitation over China is the consistent variation of rainfall in the area south of the Yangtze River valley (YRV), which accounts for 50% of the total variance and shows a significant interannual variability with 2–4-yr period (Wang and Feng, 2011; Li and Ma, 2012). This mode is closely related to the intensity of the EAWM and the El Niño–Southern Oscillation (ENSO). Strong EAWM gives rise to a dry condition in southern China, while weak EAWM results in more precipitation there (Zhou et al., 2010; Zhou, 2011). The interannal variability of winter monsoon also contains some ENSO signals (Mu and Li, 1999). Previous studies have revealed a significant inverse relationship between EAWM and ENSO. During El Niño winter, the EAWM is weakened, with a weak East Asian trough (EAT) and low-level southerly anomalies over the eastern coast of China. During La Niña winter, however, the EAT is deeper than normal, and low-level northerly anomalies occur over eastern China, favoring the southward outbreak of strong cold air, and the EAWM is largely intensified (Li, 1988, 1990; Webster and Yang, 1992; Tao and Zhang, 1998; Chen and Graf, 1998; Chen et al., 2000; Lau and Nath, 2000; Chen, 2002). On the other hand, during the mature phase of El Niño, an anomalous low-level anticyclone appears around the Philippine Sea, which is excited through the Rossby wave response. The anomalous southerly winds to the northwest side of the anticyclone not only decrease the EAWM, but also bring more moisture from the tropical ocean to southern China (Zhang et al., 1996, 1999; Wang et al., 2000; Wang and Zhang, 2002; Zhang and Sumi, 2002; Wu et al., 2003). Therefore, during the winter of warm (cold) ENSO, the EAWM tends to be weaker (stronger) than normal, and the water vapor from the Bay of Bengal and the South China Sea would converge (diverge) in southern China, favoring more (less) precipitation in this region (He et al., 2006; Zhou et al., 2010; Wang and Feng, 2011; Li and Ma, 2012).

Nevertheless, some studies have also proposed that the climate impact of La Niña shows a significant asymmetry with that of El Niño (Deser and Wallace, 1990; Hoerling et al., 1997; Wu et al., 2010; Wang et al., 2012). Zhang et al. (1996) found that the effect of El Niño on the variations of the East Asian monsoon is more significant than that of La Niña. The recent study of Wu et al. (2010) also revealed the asymmetry of the location and amplitude of the western North Pacific low-level atmospheric circulation anomalies between the El Niño and La Niña mature winters. Wang et al. (2012) investigated changes in the relationship between Meiyu rainfall over East China and La Niña events after the late 1970s, and found that the impact of La Niña on the Meiyu rainfall is not reversed to that of El Niño.

According to previous studies, the EAWM would be stronger than normal during La Niña winter, and the winter precipitation would be less than normal in southern China. However, in early 2008, the freezing rain and snow disaster over southern China just occurred during the mature phase of La Niña. In the winters of two recent La Niña events (January 2011 and January 2012), the freezing rain and snow again happened in southern China (Song, 2012). Therefore, this paper will examine the characteristics of winter precipitation anomaly in southern China and explore their possible association with warm and cold ENSO. We aim to answer the following three questions: 1) What is the relationship between the winter precipitation anomaly in southern China and ENSO? 2) Is the impact of La Niña on the winter precipitation in southern China opposite to that of El Niño? 3) Why does the freezing rain and snow in southern China occur more often during La Niña winter in recent years?

2 Data and methods

Multiple datasets are used in this study, including monthly sea surface temperature (SST) data from the Hadley Center (1948–2011), monthly atmospheric reanalysis data from the NCEP/NCAR (1948–2011), monthly precipitation anomalies over global land and oceans from the precipitation reconstruction (PREC) dataset (1948–2011; Chen et al., 2002), and monthly station rainfall data at more than 700 stations in China provided by the China Meteorological Administration (1951–2011). The climatology of the station precipitation data is from 1951 to 2011, and that of all the other gridded data is from 1948 to 2011. In this study, the winter of 2007 refers to December 2007 and January–February 2008.

There are a number of EAWM indices proposed by using different physical variables, such as the sea level pressure (SLP), the 500-hPa geopotential height, the zonal and meridional winds at lower and upper levels, and so on. However, different indices may reflect different aspects of the winter monsoon features, and the specific years with strong (weak) EAWM are often different among these indices (Guo, 1994; Zhu, 2008; Wang and Chen, 2010; Liu et al., 2012). Therefore, we select several representative EAWM indices for comparison, including: 1) the Siberian high index ($I_{\text{SLP-Gong}}$ for short; Gong et al., 2001), defined as the SLP averaged in the Siberian high region (40°–60°N, 70°–120°E); 2) the east-west land-sea pressure contrast index ($I_{\text{SLP-ChL}}$; Chan and Li, 2004), defined as the SLP difference between East Asia (30°–55°N, 100°–120°E) and the northwestern Pacific (30°–55°N, 150°–170°E); 3) the low-level meridional wind indices, including the 10-m meridional wind averaged in southeastern East Asia ((10°–25°N, 110°–130°E) and (25°–40°N, 120°–140°E)) ($I_{\text{v10-ChW}}$; Chen et al., 2000), and the 850-hPa meridional wind averaged in eastern East Asia (20°–40°N, 100°–140°E) ($I_{\text{v850-Yang}}$; Yang et al., 2002); 4) the East Asian trough index, defined as the 500-hPa geopotential height averaged in (30°–45°N, 125°–145°E) ($I_{\text{H500-Sun}}$; Sun and Li, 1997); and 5) the East Asian subtropical jet index, defined as the 300-hPa zonal wind shear between (27.5°–37.5°N, 110°–170°E) and (50°–60°N, 80°–140°E) ($I_{\text{u300-Jhun}}$; Jhun and Lee, 2004).

3 Characteristics of the winter precipitation in southern China

As revealed by previous studies, the first major mode of the interannual variability of the winter precipitation over China is the consistent variation of rainfall in the regions south of the YRV, which explains about 49.6% of the total variance (Wang and Feng, 2011). Based on the station rainfall data over 700 stations in China from 1951 to 2011, we can also obtain similar results using the empirical orthogonal function method (figure omitted). Therefore, we define a winter precipitation index (WPI) as the normalized winter precipitation averaged over all stations in six provinces south of the YRV, i.e., Hunan, Jiangxi, Zhejiang, Fujian, Guangdong, and Guangxi (Fig. 1). Based on one standard deviation of WPI (Fig. 2), there are 9 yr with abnormally more winter precipitation (1958, 1968, 1982, 1984, 1989, 1991, 1994, 1997, and 2002;

Group I for short), and 10 yr with abnormally less winter precipitation in southern China (1950, 1959, 1962, 1964, 1983, 1985, 1986, 1995, 1998, and 2008; Group II for short).

During the winter of Group I, winter precipitation is above normal over most parts of China except most parts of Northeast China, northeastern Inner Mongolia, and North Xinjiang. Winter precipitation is over 50% above normal in the regions south of the YRV (Fig. 3a). During the winter of Group II, however, less precipitation covers most areas of China, especially western and eastern Northwest China, western North China, and the regions south of the YRV. Winter rainfall anomaly is over 80% below normal in southern South China (Fig. 3b). The composite maps based on the global gridded precipitation data show similar results (Fig. 4). During the winter of Group I, precipitation is above normal in the low-mid latitudes of

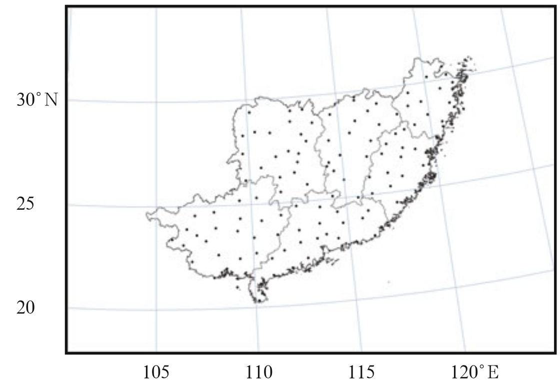

Fig. 1. Distribution of the observation stations in southern China.

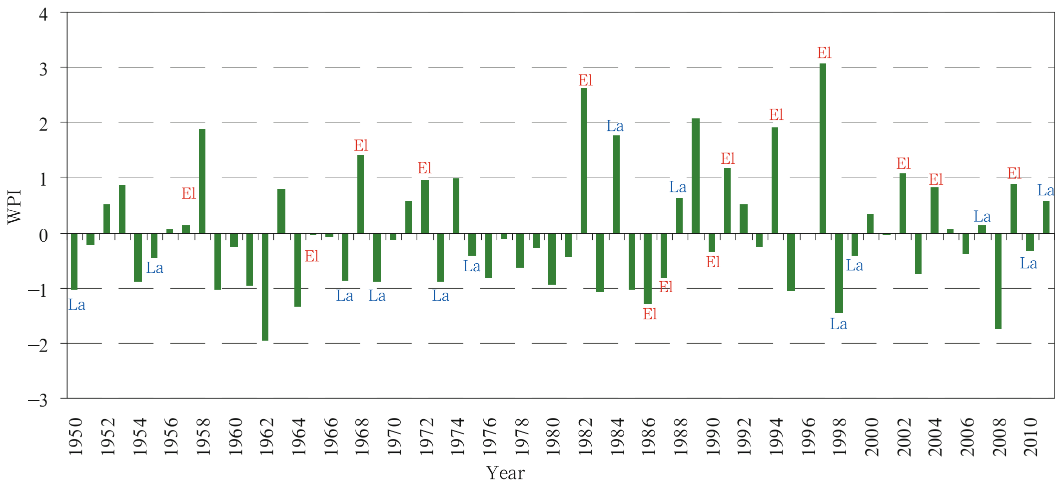

Fig. 2. Normalized time series of the winter precipitation index (WPI) in southern China (green bar). El/La indicates El Niño/La Niña event in winter.

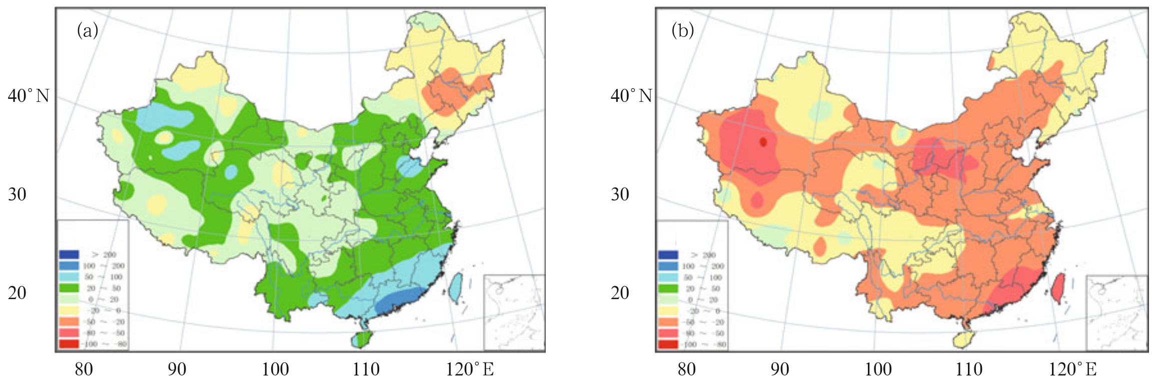

Fig. 3. Composite anomalous percentage (%) of winter precipitation in China for (a) positive winter precipitation anomaly years and (b) negative winter precipitation anomaly years in southern China (based on 700 station precipitation data in China).

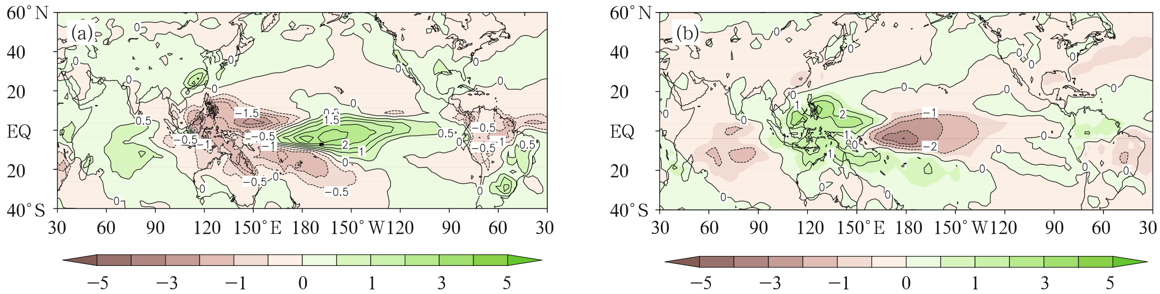

Fig. 4. As in Fig. 3, but for global precipitation anomaly (mm) based on the global gridded precipitation data.

Eurasia, with one maximum center in southern China (Fig. 4a). In the winter of Group II, however, precipitation is mostly below normal in the low-mid latitudes of Eurasia, especially in southern China (Fig. 4b).

The composite results of global precipitation also show some important features in the tropics. During the winter of Group I, precipitation is above normal in the tropical central Indian Ocean and equatorial eastern-central Pacific, and below normal in the Maritime Continent and the equatorial western Pacific (Fig. 4a). This feature is similar to the tropical precipitation anomaly pattern during El Niño mature winter (Yuan and Yang, 2012). During the winter of Group II, the anomaly pattern is just the opposite, with more winter precipitation in the Maritime Continent and the equatorial western Pacific, and less winter precipitation over the tropical central Indian Ocean and equatorial eastern-central Pacific (Fig. 4b), which is also similar to the tropical precipitation anomaly pattern during La Niña mature winter. The above feature indicates a close relationship between the winter precipitation in southern China and ENSO. However, both the station rainfall data in China and the global gridded precipitation data show that during the winter of Group I (Group II), winter precipitation is above (below) normal over most areas of China. It is different from the anomalous winter precipitation pattern with less rainfall in northern China and more rainfall in southern China (more rainfall in northern China and less rainfall in southern China) during El Niño (La Niña) winter (Gong and Wang, 1998). Therefore, we further investigate the atmospheric circulation features for Groups I and II, and explore their relationship with El Niño and La Niña by comparison.

During the winter of Group I, the Siberian high is weak, and the east-west pressure contrast is smaller than normal, with positive SLP anomaly over northwestern Pacific and negative SLP anomaly over Eurasia (Fig. 5a). In the lower troposphere, anomalous southerly winds control eastern East Asia and extend from the southeastern coast of China to Northeast Asia, indicating a weak EAWM (Fig. 5b). Since the anomalous southerly winds are located to the northwest of the low-level Philippine Sea anticyclone (PSAC), this feature denotes a close relationship between the low-level wind anomalies for Group I and the PSAC. At 500 hPa, positive anomaly of geopotential height dominates in the north and negative anomaly in the south of the mid-high latitudes of Eurasia. Both the Ural high ridge and the East Asian trough (EAT) are weaker than normal, also indicating a weak EAWM. However, positive anomaly of 500-hPa geopotential height covers the tropical regions from the tropical Indian Ocean to Pacific, indicating an enhanced western Pacific subtropical high (WPSH), with its high ridge shifting more southward and extending more westward (Fig. 5c). This feature is favorable for more water vapor transport from the tropic ocean to southern China. Therefore, the winter precipitation tends to be above normal in southern China. At 200 hPa, easterly anomalies control the regions from central China to southern Japan, while westerly anomalies cover Southeast Asia (Fig. 5d). The East Asian subtropical jet (EASJ) is thereby weaker than normal, also reflecting a weak EAWM (Yang et al., 2002; Jhun and Lee, 2004). The above analysis demonstrates that during the winter with more precipitation in southern

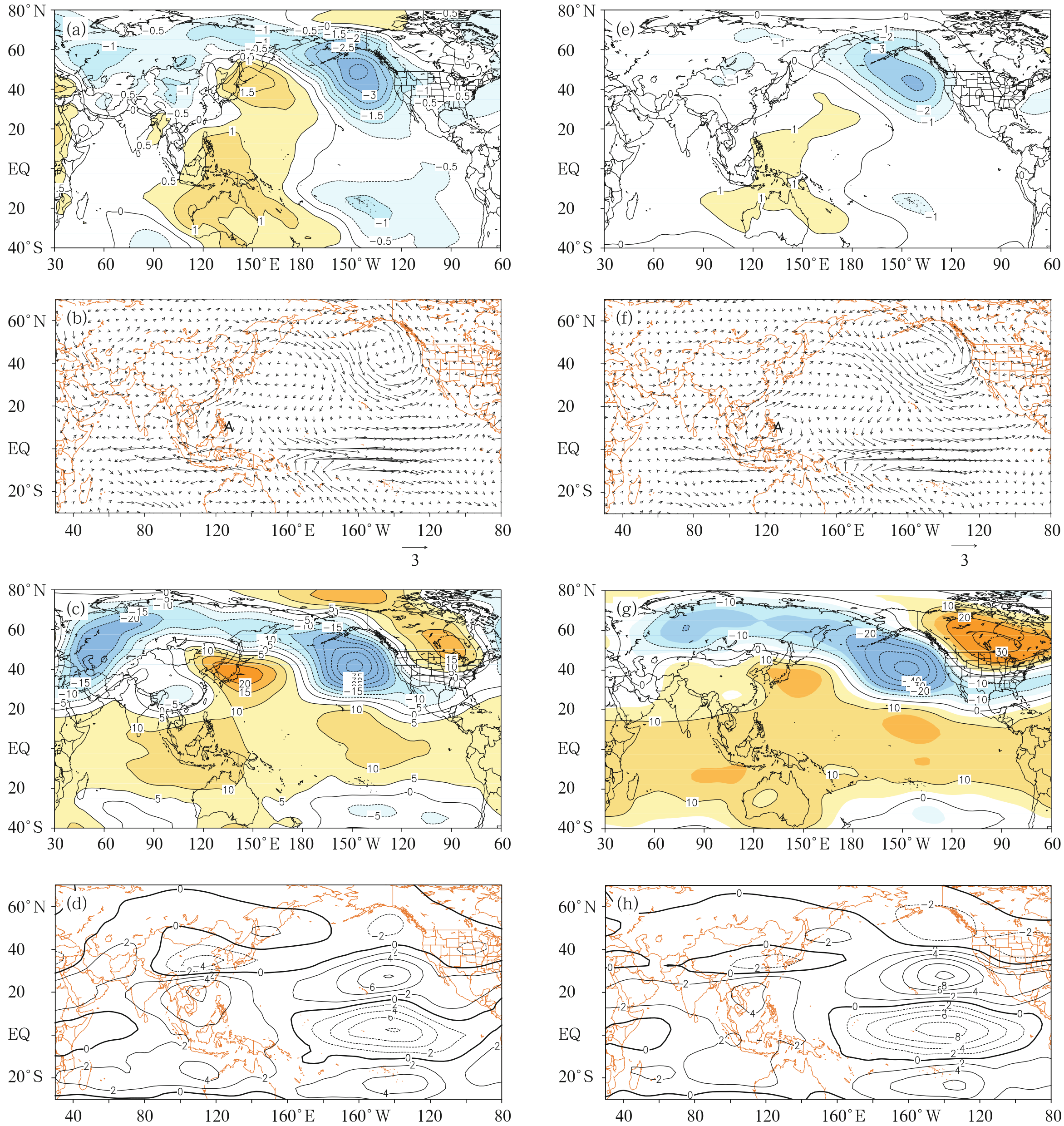

Fig. 5. Composite anomalous atmospheric circulation in winters for (a–d) exceptionally more winter precipitation anomaly years in southern China and (e–h) El Niño years during 1948–2011. (a, e) Sea level pressure (hPa), (b, f) 850-hPa wind (m s^{-1}), (c, g) 500-hPa geopotential height (gpm), and (d, h) 200-hPa zonal wind (m s^{-1}).

China (Group I), the winter monsoon circulation at different levels shows a weak EAWM. Influenced by the weak winter monsoon, anomalous southerly winds control southern China, and more moisture flux converges in that region. Therefore, more winter precipitation occurs in southern China, consistent with previous studies (Zhou and Wu, 2010; Zhou, 2011).

The atmospheric circulation anomalies for Group II (years with less winter precipitation in southern China) are approximately opposite to those of Group I. The east-west pressure contrast is larger than normal, with a stronger Siberian high and negative anomaly of SLP over North Pacific (Fig. 6a). Anomalous low-level northerly winds prevail over eastern East Asia (Fig. 6b). The 500-hPa geopotential height over Eurasia displays a positive anomaly in the west and a negative anomaly in the east. The Ural high ridge is intensified and the EAT is deeper than normal, indicating a strong EAWM. Meanwhile, the 500-hPa geopotential height is near normal over the tropical Indian Ocean and Pacific (Fig. 6c), denoting that the WPSH is near normal. At 200 hPa, the EASJ is stronger than normal and moves more southward (Fig. 6d), unfavorable for more precipitation in southern China in winter (Mao et al., 2007). Therefore, during the winter with less precipitation in southern China, the atmospheric circulation over Eurasia shows a strong EAWM at different levels. Influenced by the anomalous cold and dry northerly winds, winter precipitation is less than normal in southern China.

We also calculate the linear correlation between WPI and atmospheric circulation anomaly at different levels. Significant negative correlation of SLP is observed over the Lake Balkhash (Fig. 7a), indicating

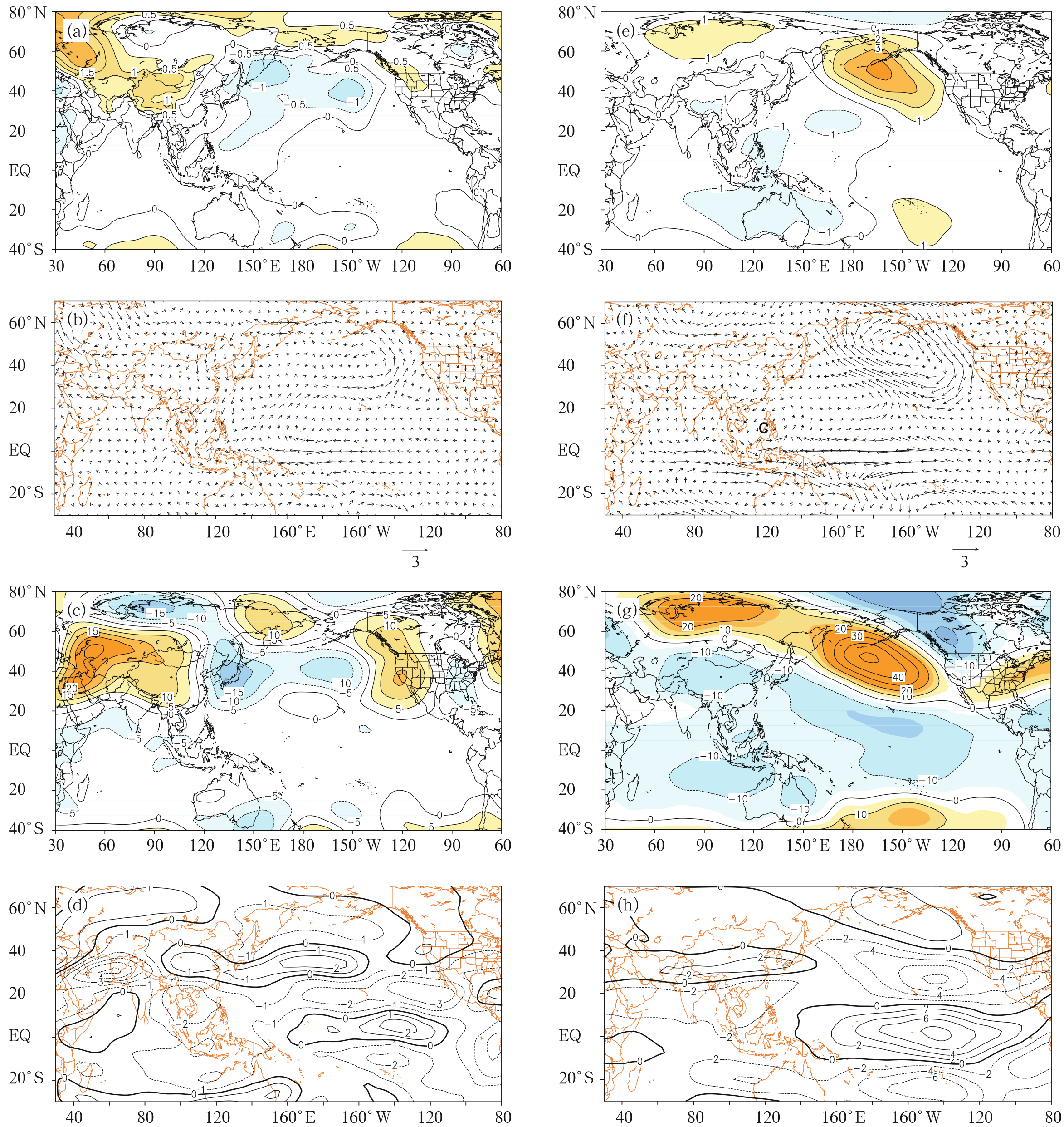

Fig. 6. As in Fig. 5, but for (a–d) exceptionally less winter precipitation anomaly years and (e–h) La Niña years during 1948–2011.

that when the Siberian high is stronger (weaker) than normal, winter precipitation tends to be less (more) than normal in southern China. Meanwhile, significant positive correlation of SLP in northwestern Pacific and negative correlation over tropical eastern Pacific (Fig. 7a) may reflect the "seesaw" relationship of the pressure between the tropical eastern and western Pacific, i.e., the southern oscillation. This feature denotes a possible connection between ENSO and the SLP anomaly influencing the winter precipitation in southern China. In the lower troposphere, the meridional wind over East Asia is significantly correlated with WPI (Fig. 7b), suggesting that when anomalous southerly (northerly) winds control East Asia, winter precipitation would be more (less) than normal in southern China (Zhang et al., 1996; Wang and Feng, 2011). Meanwhile, the significant correlation of zonal wind over the tropical ocean also indicates the possible connection of the winter precipitation in southern China with SST over the tropical ocean. Significant negative correlation of 500-hPa geopotential height is observed near the Ural Mountains, and significant positive correlation is located over the regions of the EAT (Fig. 7c). Therefore, when the Ural high ridge is weaker (stronger) and the EAT is shallower (deeper), more (less) winter precipitation tends to occur in southern China. The significant correlation of the 500-hPa geopotential height over the tropical Indian-Pacific Ocean with WPI also suggests that the intensity and position of the WPSH should have significant impacts on the winter precipitation in southern China. In the upper troposphere, the 200-hPa zonal wind over the subtropical region in East Asia is significantly negatively correlated with WPI (Fig. 7d), reflecting that the winter precipitation in southern China may be more (less) than normal when the westerly jet is weakened (intensified). The above correlation results are consistent with our previous composite analysis (Figs. 5 and 6), further confirming that a stronger (weaker) EAWM would result in less (more) winter precipitation in southern China (Zhou and Wu, 2010; Wang and Feng, 2011; Zhou, 2011).

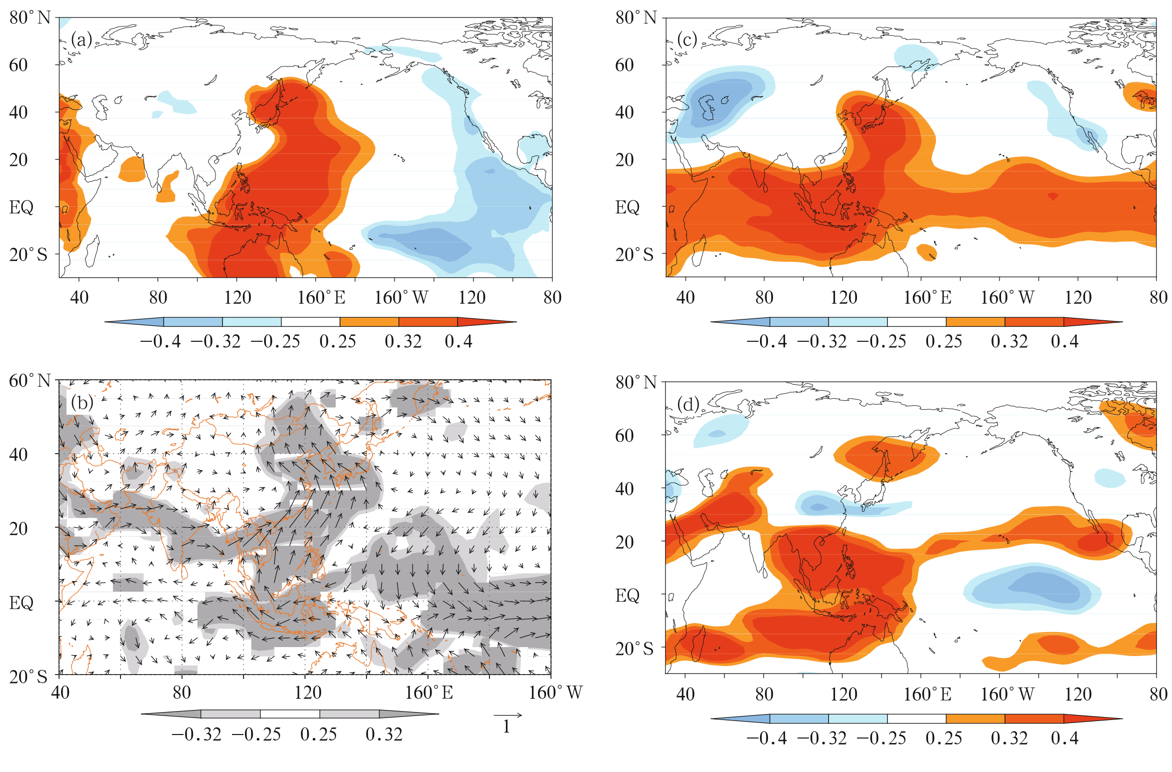

Fig. 7. Correlation between WPI and anomalous atmospheric circulations. (a) SLP, (b) 850-hPa wind, (c) 500-hPa geopotential height, and (d) 200-hPa zonal wind. Shading denotes areas with correlation above the 95% confidence level.

Since different winter monsoon indices may reflect different features of the EAWM (Guo, 1994; Zhu, 2008; Liu et al., 2012), we calculate some representative indices for the composites of Group I and Group II. All indices show a consistent weak (strong) EAWM circulation pattern during more (less) winter precipitation years in southern China: the Siberian high is weakened (enhanced), the east-west land-sea pressure contrast is smaller (larger), anomalous southerly (northerly) winds prevail over East Asia, the EAT is shallower (deeper) than normal, and the East Asian subtropical jet is weakened (strengthened) (Table 1).

Table 1. Values of various East Asian winter monsoon indices composite for years of exceptionally more (Group I) and less (Group II) winter precipitation anomalies in southern China

	$I_{\text{SLP-Gong}}$	$I_{\text{SLP-ChL}}$	$I_{\text{v10-ChW}}$	$I_{\text{v850-Yang}}$	$I_{\text{H500-Sun}}$	$I_{\text{u300-Jhun}}$
Group I	–0.73	–1.94	0.49	0.51	18.85	–3.05
Group II	0.75	1.36	–0.29	–0.44	–15.15	0.77

4 Relationship between the winter precipitation in southern China and ENSO

Analyses in the previous section have revealed some ENSO signals in the atmospheric circulation anomalies associated with winter precipitation anomaly in southern China, such as SLP in the tropical oceans and low-level winds over East Asia. In this section, we further explore the relationship between warm/cold ENSO and the winter precipitation anomaly in southern China. Considering the decadal change of the SST anomaly (SSTA) distribution during ENSO mature phase in recent 10 years (Ashok et al., 2007; Kao and Yu, 2009; Kug et al., 2009; Yeh et al., 2009; Lee and McPhaden, 2010), we select all El Niño and La Niña years from 1948 to 2011 based on one standard deviation of Niño3, Niño4, and Niño3.4 indices in winter. There are 14 El Niño years: 1957, 1965, 1968, 1972, 1982, 1986, 1987, 1990, 1991, 1994, 1997, 2002, 2004, and 2009; and 14 La Niña years: 1949, 1950, 1955, 1967, 1970, 1973, 1975, 1984, 1988, 1998, 1999, 2007, 2010, and 2011. When these ENSO years are marked on the WPI in Fig. 2, we obtain some implications: 1) during most El Niño winters (71.4% of all El Niño years), winter precipitation is above normal in southern China, and during most La Niña winters (69.2% for all La Niña years), winter precipitation is below normal in southern China; 2) some winters with more precipitation in southern China are not El Niño years, such as 1958 and 1989; similarly, some winters with less precipitation in southern China do not occur in La Niña years, such as 1962, 1964, 1995 and 2008; 3) before 1980, the probability of El Niño winters with more precipitation in southern China is 75%, which changes a little to 70% after 1980; however, the probability of La Niña winters with less precipitation in southern China is 100% before 1980 and largely reduces to only 42.9% after 1980.

The composite atmospheric circulation anomalies during El Niño and La Niña years are also shown in Figs. 5 and 6, so that we can compare their features with the composite results for Groups I and II, respectively. It is shown that the composite circulation anomalies for El Niño years are similar to those during the winters with more precipitation in southern China (Group I). The Aleutian low is intensified and the east-west land-sea pressure contrast is smaller than normal (Fig. 5e), similar to Fig. 5a. An anomalous low-level anticyclone appears around the Philippine Sea and anomalous southerly winds control the eastern coast of China. Meanwhile, anomalous easterlies are observed over the equatorial Indian Ocean, and anomalous westerlies prevail over the equatorial central-western Pacific (Fig. 5f), also similar to Fig. 5b. The 500-hPa geopotential height over Eurasia displays an anomalous "negative in the north and positive in the south" pattern, with a weak Ural high ridge and a shallower EAT. At the same time, significant positive anomaly of geopotential height covers the tropical region, indicating an enhanced WPSH with its high ridge extending more westward and southward (Fig. 5g). During El Niño winters, features of positive anomalies of the 500-hPa geopotential height over the tropical region are more significant (Fig. 5g). However, during the winters with more precipitation in southern China, more significant features of the geopotential height anomalies appear over the mid-high latitudes of Eurasia (Fig. 5c). At 200 hPa, the East Asian subtropical jet is weaker than normal (Fig. 5h; Zhang et al., 1996), also similar to Fig. 5d. Larger similarities between the right panel and the left panel confirm that El Niño is an important external forcing factor resulting in more winter precipitation in southern China (Li, 1988, 1990; Tao and Zhang, 1998; Wu et al., 2003; Zhou and Wu, 2010; Zhou et al., 2010).

However, the composite atmospheric circulations for La Niña winters show more differences with Group II (winters with less precipitation in southern China). During La Niña winters, the Aleutian low is weaker than normal. However, few signals of SLP anomaly can be discerned around the Siberia and for the east-west land-sea pressure contrast (Fig. 6e), different from the intensified Siberian high and larger east-west pressure contrast for Group II (Fig. 6a). At 850 hPa, an anomalous cyclone is located around the Philippines, and anomalous easterlies prevail over southern China. Meanwhile, westerly anomalies cover the equatorial Indian Ocean, and easterly anomalies dominate over the equatorial western Pacific (Fig. 6f). All these features are different from those for Group II (Fig. 6b). The 500-hPa geopotential height over Eurasia shows an anomalous "positive in the north and negative in the south" pattern, indicating a strong EAWM. Negative anomaly of 500-hPa geopotential height covers the tropical Indian-Pacific Ocean, denoting a weak WPSH with its high ridge retreating more eastward (Fig. 6g). These features are also different from Fig. 6c. At 200 hPa, westerly anomalies cover from northern India to southern Japan during La Niña winters, indicating an intensified East Asian subtropical jet (Fig. 6h). Although the subtropical jet is also enhanced for Group II, the Middle East jet is weakened (Fig. 6d), different from that in Fig. 6h.

Significant positive correlations of SSTA with WPI are located over the tropical Indian Ocean and the equatorial eastern-central Pacific (Fig. 8a), denoting a close relationship between ENSO and winter precipitation in southern China. However, the composite SSTA for Groups I and II shows significant differences compared with the correlation results. During the winter of Group I, an El Niño event occurs over the equatorial eastern-central Pacific. Meanwhile, SSTA is above normal in the tropical Indian Ocean and below normal over the equatorial western Pacific (Fig. 8b). These features are consistent with the SSTA distribution pattern during El Niño winter (figure omitted). However, during the winter of Group II, except weak negative SSTA dominating over the equatorial eastern-central Pacific, SST over other oceans shows insignificant anomaly features (Fig. 8c).

The above analysis not only confirms the close relationship between more winter precipitation in southern China and El Niño events, but also suggests that

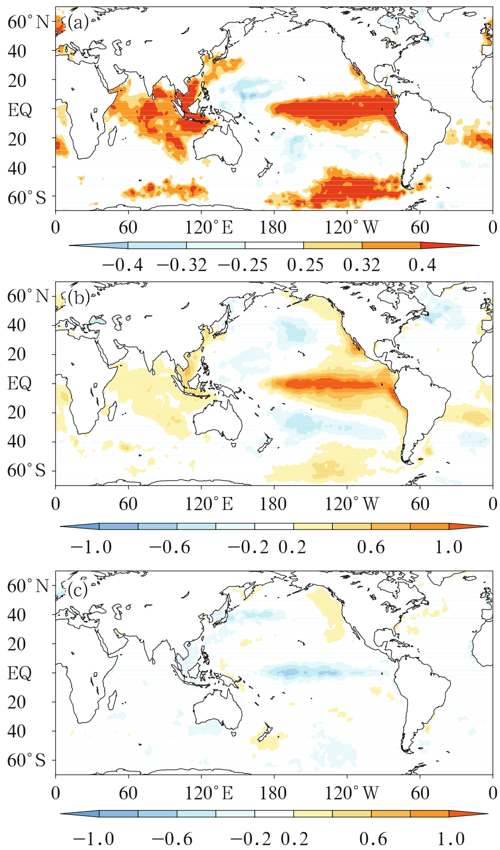

Fig. 8. (a) Significant correlation (above the 95% confidence level) between WPI and the global SSTA, and SSTA composite (°C) for (b) more winter precipitation (Group I) and (c) less winter precipitation (Group II) years in southern China.

the relationship between less winter precipitation in southern China and La Niña events is not significant. The impact of La Niña on the winter precipitation in southern China should not be opposite to that of El Niño. Therefore, in the following section, we further investigate the impact of La Niña on the winter precipitation in southern China and the associated physical mechanisms.

5 Decadal variability of the La Niña impact on winter precipitation in southern China

It is revealed in previous sections that the probability of less winter precipitation in southern China during La Niña years changes from 100% before 1980 to 42.9% after 1980, suggesting that La Niña years with more winter precipitation in southern China take a larger probability (57.1%) after 1980. Then, does the impact of La Niña on the winter precipitation in southern China show a decadal variability?

Figure 9 shows the composite anomalous percentage of winter precipitation over 700 stations in China during El Niño and La Niña years. Few differences can be observed for El Niño years before and after 1980. They both show less precipitation over central China and more precipitation over eastern China and the regions south of the YRV (Figs. 9a and 9b). However, the composite precipitation for La Niña years exhibits significant differences before and after 1980. During La Niña winters before 1980, less precipitation occurs over most China, with minimum centers over western China and the regions from North China to the middle and lower reaches of the YRV (Fig. 9c). During La Niña winters after 1980, however, more precipitation dominates over some regions of China, especially in eastern Northwest China and southern China (Fig. 9d). We have also compared the temperature anomaly over China for La Niña years before and after 1980. During La Niña winters before 1980, temperature is below normal over most China. After 1980, however, except Northwest China and southern China with low temperature, winter temperature is above normal in other regions (figure omitted). This feature probably indicates the variation of La Niña impact on the winter

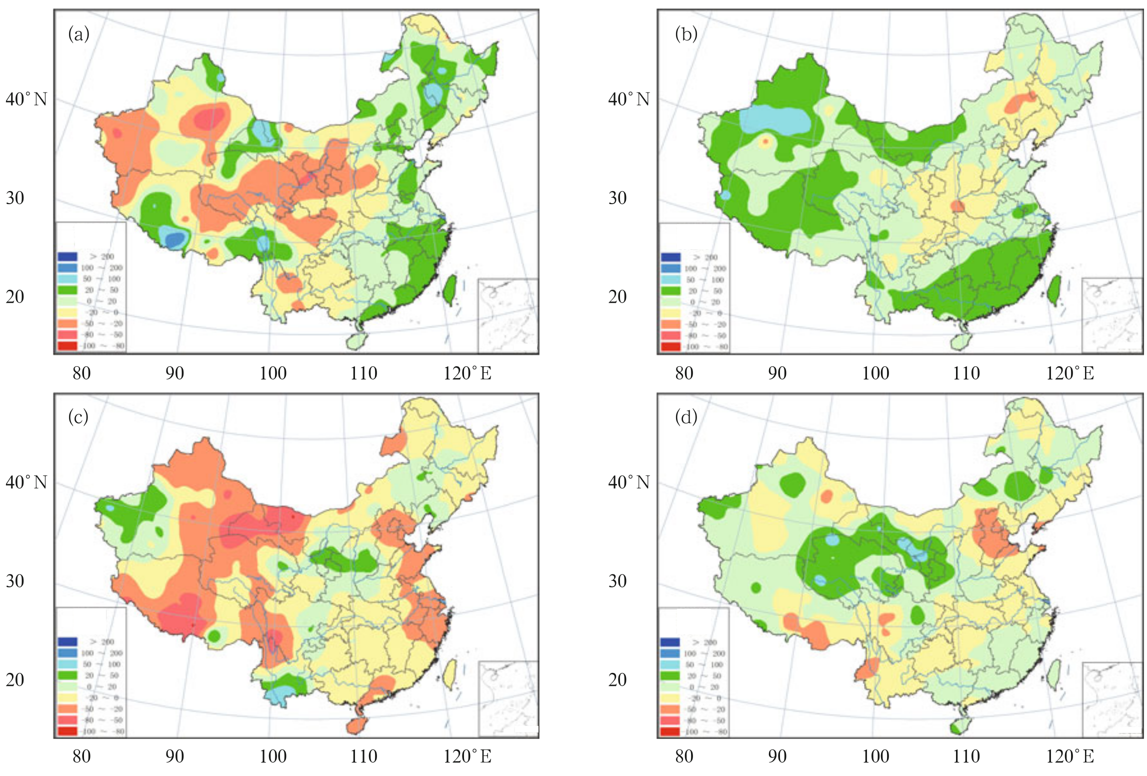

Fig. 9. Composites of anomalous percentage (%) of winter precipitation in China for El Niño and La Niña years. (a) El Niño years before 1980, (b) El Niño years after 1980, (c) La Niña years before 1980, and (d) La Niña years after 1980.

temperature in China influenced by the global warming background (not discussed in this paper). More importantly, since the temperature is still below normal in southern China during La Niña winter after 1980 and more winter precipitation tends to occur in southern China, this feature results in somewhat cold and wet winter in southern China during La Niña winters after 1980, but not cold and dry winter before 1980. Therefore, freezing rain and snow/ice storms become more likely to occur in southern China during La Niña winters after 1980.

We further compare the atmospheric circulation anomalies at different levels for La Niña years before and after 1980, respectively. During La Niña winters before 1980, the SLP anomaly over Eurasia shows a "positive in the north and negative in the south" pattern (Fig. 10a). After 1980, however, positive anomaly of SLP dominates over the Siberia, indicating an intensified Siberian high (Fig. 10f). Before 1980, the anomalous low-level cyclone excited by La Niña is located to the east of the Philippines, causing anomalous northerly winds over southern China (Fig. 10b). After 1980, however, the anomalous low-level cyclone induced by La Niña moves to the west of the Philippines. Therefore, anomalous easterly winds dominate over southern China (Fig. 10g), not conducive to the strengthening of the winter monsoon, but favorable for more moisture flux transport from northwestern Pacific to southern China.

At 500 hPa, the geopotential height in Eurasia shows an anomalous "positive in the north and negative in the south" pattern, reflecting a strong EAWM during La Niña winter before 1980. Meanwhile, negative anomaly of 500-hPa geopotential height covers the tropical and subtropical regions of Eurasia (Fig. 10c). This feature indicates a weakened WPSH with its high ridge retreating more eastward, unfavorable for the water vapor transport from the tropical oceans to southern China. During La Niña winters after 1980, the 500-hPa geopotential height shows a weak "positive in the north and negative in the south" pattern over Eurasia. However, positive anomaly of the geopotential height over eastern East Asia suggests a shallower EAT, which is unfavorable for the southward invasion of cold air to southern China. Meanwhile, the 500-hPa geopotential height is relatively below normal over the Bay of Bengal (Fig. 10h). Therefore, the India-Burma trough would be intensified, favoring more moisture flux transport from the Indian Ocean to southern China.

In the upper troposphere, the East Asian subtropical jet is strengthened during La Niña winter both before and after 1980. However, the strengthened jet is located over southern China before 1980 (Fig. 10d), unfavorable for more winter precipitation there. During La Niña winters after 1980, however, the westerly jet moves more northward and southern China is located under the right side of the jet entrance area (Fig. 10i). Therefore, more winter precipitation would occur in southern China through the secondary vertical circulation (Mao et al., 2007).

During La Niña winters before 1980, anomalous divergence of moisture flux controls southern China (Fig. 10e). After 1980, however, anomalous convergence of moisture flux dominates over southern China. Intensified moisture flux comes from the tropical Indian Ocean and western Pacific (Fig. 10j), with the former caused by the enhanced India-Burma trough and the latter induced by the anomalous easterlies to the north side of the anomalous low-level cyclone.

The above analyses confirm that the impact of La Niña on the winter precipitation in southern China exhibits a significant decadal variability. During a La Niña winter before 1980, the East Asian subtropical jet is stronger than normal and the jet is located more southward. The EAT is deeper than normal and the WPSH is weakened with its high ridge retreating more eastward. The anomalous low-level cyclone excited by La Niña is located to the east of the Philippines, inducing anomalous northerly winds over southern China. Therefore, the intensified EAWM as well as the poor moisture flux condition would cause low temperature and less winter precipitation in southern China, i.e., a "cold and dry" winter. During a La Niña winter after 1980, however, the East Asian subtropical jet moves northward. The EAT is shallower than normal, unfavorable for the southward invasion of the winter monsoon. On the other hand, the enhanced India-Burma

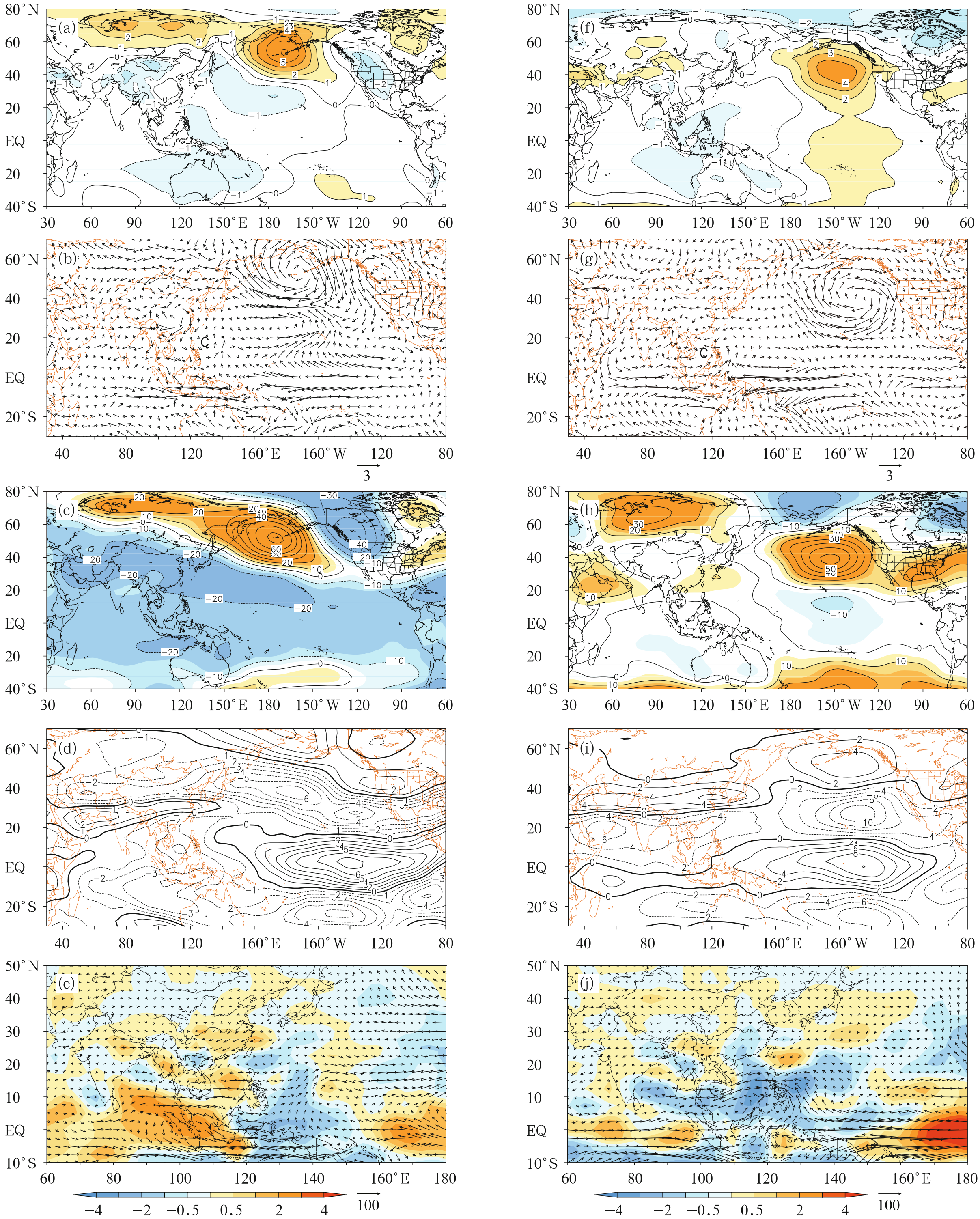

Fig. 10. Composites of the anomalous atmospheric circulation in winter for La Niña years (a–e) before 1980 and (f–j) after 1980. (a, f) SLP (hPa), (b, g) 850-hPa wind (m s^{-1}), (c, h) 500-hPa geopotential height (gpm), (d, i) 200-hPa zonal wind (m s^{-1}), and (e, j) integrated moisture flux from 1000 to 300 hPa (vector; kg s^{-1} m^{-1}) as well as convergence (blue shading; 10^{-5} kg s^{-1} m^{-2}) and divergence (yellow shading; 10^{-5} kg s^{-1} m^{-2}).

trough leads to more moisture flux from the tropical Indian Ocean. Meanwhile, the anomalous low-level cyclone excited by La Niña is located to the west of the Philippines, which also favors more moisture flux from the western Pacific to southern China. As a result, unlike the "cold and dry" winter in southern China during La Niña winter before 1980, an anomalous "cold and wet" winter occurs in southern China during La Niña winter after 1980. Therefore, the freezing rain and snow/ice storms are more likely to happen in southern China after 1980.

Considering the different external forcing patterns between El Niño and La Niña episodes, the physical mechanism for more winter precipitation in southern China during La Niña years after 1980 should not be the same as that during El Niño years. Previous studies have clearly revealed the physical mechanism of the El Niño impact on the increased winter precipitation in southern China (Zhang et al., 1999; Chang et al., 2000; Wang Bin et al., 2008; Yuan and Yang, 2012). Influenced by the warm SSTA over the equatorial eastern-central Pacific during El Niño winter, anomalous rising motion dominates over the equatorial eastern-central Pacific and anomalous subsidence prevails over the equatorial western Pacific. This subsidence also excites anomalous upward motion over southern China through the regional Hadley circulation in East Asia (Fig. 11a; Zhang et al., 1996; Yuan and Yang, 2012). On the other hand, El Niño also stimulates an anomalous low-level anticyclone around the Philippines (PSAC), which causes anomalous southerly winds over southern China. This feature not only decreases the EAWM, but also favors more moisture flux transport from western Pacific to southern China (Zhang et al., 1996, 1999; Wang et al., 2000; Zhou and Wu, 2010; Zhou et al., 2010). Therefore, El Niño would result in more winter precipitation in southern China mainly through influencing the regional Hadley circulation over East Asia and exciting the PSAC (Fig. 12a). During La Niña winter, the cold SSTA over the equatorial central Pacific and warm SSTA over the equatorial western Pacific would intensify the Walker

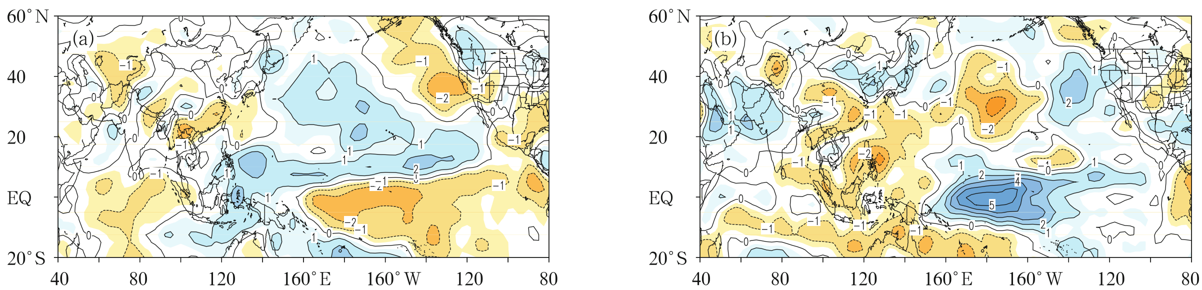

Fig. 11. Composite of the anomalous 500-hPa vertical velocity in winter for (a) El Niño years and (b) La Niña years after 1980. The vertical velocity has been multiplied by 100. Blue (yellow) shading indicates anomalous descending (ascending) motion (0.01 Pa s^{-1}).

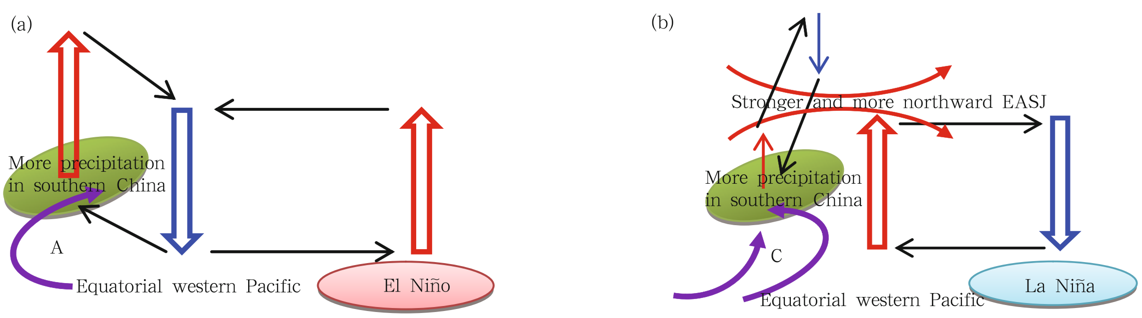

Fig. 12. Sketch map for the physical mechanism of the (a) El Niño and (b) La Niña impact on the winter precipitation in southern China after 1980.

circulation. According to our analysis, La Niña events after 1980 would increase the East Asian subtropical jet and cause the jet moving more northward. Since southern China is located under the right side of the jet entrance region, the anomalous subsidence to the left side of the jet (North China) would induce anomalous rising motion in southern China (Fig. 11b). On the other hand, La Niña after 1980 would also increase the India-Burma trough and excite the low-level Philippine Sea cyclone (PSC) to the west of the Philippines. More moisture flux transports from the tropical Indian Ocean and western Pacific to southern China, favoring more winter precipitation there. Therefore, La Niña after 1980 may also induce more winter precipitation in southern China mainly through influencing the intensity and position of the EASJ, the India-Burma trough, and the position of the PSC (Fig. 12b). It can be concluded that under the global warming background, both El Niño and La Niña would result in more winter precipitation in southern China. However, the physical mechanisms for the anomalous rising motion over southern China as well as the moisture transport are significantly different between El Niño and La Niña.

It is also revealed from the above analysis that there are three differences in the atmospheric circulation anomaly during La Niña winter before and after 1980: 1) the location of the PSC, 2) the 500-hPa geopotential height anomaly in East and South Asia, and 3) the position of the EASJ. SSTA composite shows that La Niña after 1980 (Fig. 13b) is stronger than that before 1980 (Fig. 13a). Meanwhile, the negative SSTA center during La Niña after 1980 moves westward to near the date line, and positive SSTA appears over southeastern and northwestern Pacific (Fig. 13b), showing some central-Pacific (CP) type features after 1980 (Yuan and Yan, 2013). Some recent research has found that the anomalous low-level Philippine Sea anticyclone excited by CP El Niño is located to the west of the Philippines, unlike the anticyclone induced by eastern-Pacific (EP) El Niño to the east of the Philippines (Feng and Li, 2011; Yuan and Yang, 2012; Yuan et al., 2012). Similar to this feature, the response of low-level atmospheric circulation to different types of La Niña should also be different. Because of the higher-frequency occurrence of CP La Niña after 1980 (Yuan and Yan, 2013), the anomalous low-level Philippine Sea cyclone also moves westward to the west of the Philippines (Fig. 10g). Therefore, the change of the cyclone's position should be related to the decadal variation of the SSTA distribution of La Niña during its mature phase.

On the other hand, both SST and atmospheric circulation show a decadal variability after 1980. After 1980, significant warming appears over the tropical Indian Ocean and Northwest Pacific (Fig. 14a), which results in a weak warm condition in the tropical Indian Ocean during La Niña mature phase (Fig. 13b), not a cold condition as revealed by previous studies (Klein et al., 1999; Lau and Nath, 2003; Yang et al., 2007). Coupled with the warming conditions over the tropical Indian-western Pacific Ocean, westerly winds increase over the equatorial Indian Ocean and easterlies also strengthen over the western Pacific, which lead to enhanced convergence and a cyclone around southern South China Sea (Fig. 14b). Therefore, decadal warming over the tropical Indian–western Pacific Ocean not only favors the westward movement of the PSC excited by La Niña, but also increases the moisture condition for more precipitation in southern China. At 500 hPa, the geopotential height has significantly intensified over the tropical and subtropical regions of Eurasia (including the region of the EAT) after 1980. However, the geopotential height over the Ural decreases to some extent (Fig. 14c). These features may reflect the decadal decrease of the EAWM after 1980 (Zhu, 2008; Wang and Chen, 2010). At 200 hPa, westerly winds cover the regions from central Asia to southern Japan in the difference map (Fig. 14d), indicating a significant decadal increase of the EASJ. Therefore, besides the decadal variation of the SSTA distribution of La Niña, the decadal variation of the atmospheric circulation in the Northern Hemisphere should also be an important reason for more winter precipitation in southern China during La Niña winter after 1980.

6 Conclusions and discussion

Using atmospheric circulation data from NCEP/

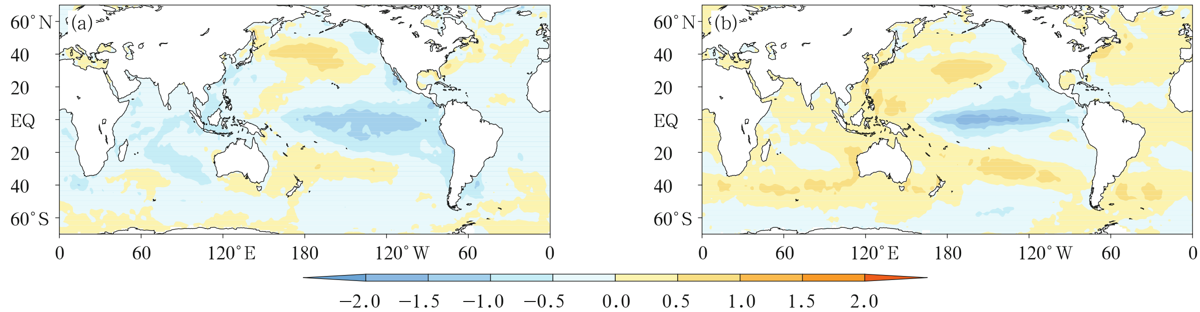

Fig. 13. SSTA (℃) composite in winter for La Niña year (a) before 1980 and (b) after 1980.

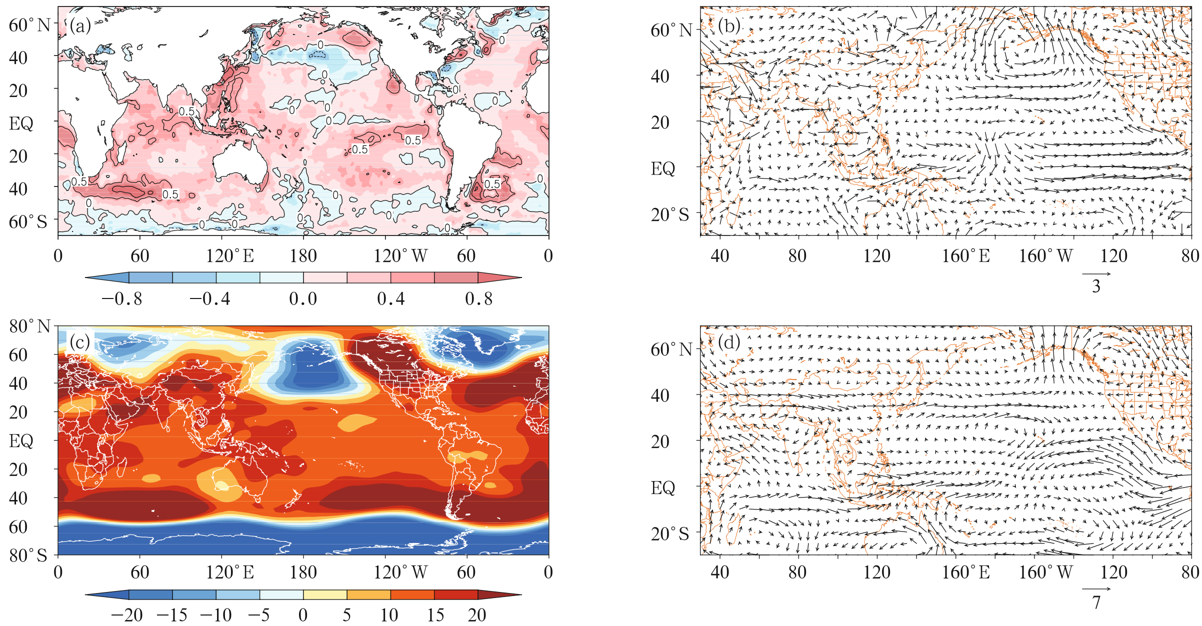

Fig. 14. Decadal variability (average of 1980–2011 minus average of 1948–1979) of (a) SST (℃), (b) 850-hPa wind (m s^{-1}), (c) 500-hPa geopotential height (gpm), and (d) 200-hPa wind (m s^{-1}) in winter.

NCAR, SST data from the Hadley Center, station rainfall data over 700 stations in China, and global gridded precipitation data, this paper has investigated the EAWM and the atmospheric circulation anomalies during exceptionally more and less winter precipitation years in southern China, and further explored their asymmetric relations with El Niño and La Niña. We have basically answered the three questions proposed in the introduction section: 1) What is the relationship between the winter precipitation anomaly in southern China and ENSO events? During more winter precipitation years in southern China, there is usually a significant El Niño event maturing in the equatorial eastern-central Pacific. During the El Niño mature phase, more winter precipitation tends to occur in southern China. The composite atmospheric circulation patterns show much similarity for more winter precipitation years in southern China and for El Niño winters, which confirms that El Niño is an important external forcing factor for more winter precipitation in southern China. However, during less winter precipitation years in southern China, few La Niña signals can be discerned over the equatorial Pacific. 2) Is the impact of La Niña on the winter precipitation in southern China opposite to that of El Niño? The answer is no. El Niño would result in more winter precipitation in southern China. However, the impact of La Niña on the winter precipitation in southern China shows a decadal variability. During La Niña winter before 1980, the EAWM is significantly stronger than normal, and the WPSH is weakened with its high ridge retreating more eastward. Thereby, anomalous northerly winds control southern China and cause a "cold and dry" winter there. However, during La Niña winter after 1980, the intensity of EAWM is largely reduced as compared with the condition before 1980, whereas the tropical moisture flux increases significantly. As a result, more winter precipitation occurs in southern China, which induces a "cold and wet" winter there. 3) Why does the freezing rain and snow in southern China occur more often during La Niña winter in recent years? During La Niña winter after 1980, the EASJ is intensified and moves northward. Since southern China is located to the right side of the jet entrance, anomalous rising motion dominates over southern China through the secondary vertical circulation. Meanwhile, the East Asian trough is weaker than normal, unfavorable for the southward invasion of the cold air. The intensified India-Burma trough favors more moisture flux transport from the tropical Indian Ocean to southern China. The anomalous low-level cyclone excited by La Niña is located to the west of the Philippines, causing anomalous easterlies over southern China and favoring more moisture from northwestern Pacific to southern China. Therefore, during La Niña winter after 1980, the freezing and snow storm disasters are more likely to occur in southern China. We have also analyzed some La Niña cases with more winter precipitation in southern China after 1980 (such as 1984, 1988, 2007, and 2011), and found that the winter monsoon circulation features in each case are similar to our composite results. Our further analyses have pointed out that the high-frequency occurrence of CP La Niña after 1980 causes the low-level anomalous cyclone to move to the west of the Philippines.

On the other hand, the atmospheric circulations over the tropical and subtropical Eurasia show significant decadal variability after 1980. We have also checked the possible impact of the decadal variability of the atmospheric circulation background through changing the climatology. Based on the climatology of 1980–2011, the anomaly features of both the station precipitation in China and the atmospheric circulation over East Asia show evident differences as compared with those based on the climatology from 1948 to 2011 (figures omitted). It is therefore inferred that the decadal variability of the climate background should have some effects on the decadal variation of La Niña impact on the winter precipitation in southern China. To conclude, the change of the SSTA distribution type of La Niña during its mature phase, as well as the decadal variability of the atmospheric circulation in the Northern Hemisphere are the important reasons for the decadal variation of the La Niña impact on the East Asian climate after 1980.

It should be noted that the decadal change of the La Niña impact on the tropical atmosphere, especially on the anomalous low-level cyclone around the Philippines and the tropical moisture transport, may be more direct and significant. The atmospheric circulation anomaly over the mid-high latitudes of Eurasia in winter may be influenced by some other factors, such as the Arctic Oscillation (Gong et al., 2001), the North Atlantic Oscillation (Wu and Huang, 1999), the Arctic sea ice (Wu et al., 2011), the snow cover over Eurasia (Zuo et al., 2011), and so on. Further investigations are still needed to explore the circulation anomalies over the mid-high latitudes of Eurasia associated with winter precipitation anomalies in southern China.

Our analysis reveals that winter precipitation is above normal over most parts of China during more winter precipitation years in southern China. However, more precipitation over southern China mainly occurs in the next January and February. It is also revealed that the "cold and wet" winter in southern China is only significant in January during La Niña winter after 1980, and the atmospheric circulation in the decaying January of La Niña is most similar to that in the whole winter of La Niña. In recent years, the freezing rain and snow storm disasters also happen more in the decaying January of La Niña, like January 2008, January 2011, and January 2012. Therefore, the above features are probably related to the subseasonal variation of the EAWM and the low-frequency activities of atmospheric circulations (Bueh et al., 2008;

Wang Yun et al., 2008; Shao et al., 2011).

Some previous studies have proposed the asymmetry of El Niño and La Niña impact on the climate. For example, Zhang et al. (1996) found that the East Asian monsoon shows significant anomaly during El Niño mature phase, while exhibits negligible anomaly during La Niña mature phase. Recently, Wu et al. (2010) revealed that the response of the atmospheric circulation anomaly over the northwestern Pacific to La Niña events is asymmetric to that of El Niño. Neither the intensity nor the position of the anomalous low-level Philippine Sea cyclone excited by La Niña is consistent with those of the anticyclone excited by El Niño. Wang et al. (2012) also suggested that La Niña events after 1970 may induce more Meiyu in the YRV, not opposite to the impact of El Niño. It is also revealed from our analysis that the impact of La Niña on the winter precipitation over southern China shows evident asymmetric features with that of El Niño. Considering the complication of La Niña impact on the climate under the global warming background, the impact deserves more studies in near future.

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REFERENCES

Ashok, K., S. K. Behera., S. A. Rao., et al., 2007: El Niño Modoki and its possible teleconnection. *J. Geophys. Res.*, **112**(C11), C11007, doi: 10.1029/2006JC003798.

Bueh Cholaw, Ji Liren, and Shi Ning, 2008: On the medium-range process of the rainy, snowy and cold weather of South China in early 2008. Part I: Low-frequencey waves embedded in the Asian-African subtropical jet. *Climatic Environ. Res.*, **13**(4), 419–433. (in Chinese)

Chan, J. C. L., and C. Y. Li, 2004: The East Asian winter monsoon. *East Asian Monoon*, Chang, C. P., Ed., World Scientific Publishing Co. Pet. Ltd., 54–106.

Chang, C. P., Y. S. Zhang, and T. Li, 2000: Interannual and interdecadal variations of the East Asian summer monsoon and tropical Pacific SSTs. Part I: Roles of the subtropical ridge. *J. Climate*, **13**, 4310–4325.

Chen Longxun, Zhu Qiangen, Luo Huibang, et al., 1991: *East Asian Monsoon.* China Meteorological Press, Beijing, 362 pp. (in Chinese)

Chen, M. Y., P. P. Xie, J. E. Janowiak, et al., 2002: Global land precipitation: A 50-yr monthly analysis based on gauge observations. *J. Hydrometeor.*, **3**, 249–266.

Chen Wen, 2002: Impact of El Niño and La Niña on the cycle of East Asian winter and summer monsoon. *Chinese J. Atmos. Sci.*, **26**(5), 595–610. (in Chinese)

——, and H. F. Graf, 1998: The Interannual Variability of East Asian Winter Monsoon and Its Relation to Global Circulation. Max-Planck-Institute fuer Meteorologic Report No. 250, 1–35.

——, ——, and Huang Ronghui, 2000: The interannual variability of East Asian winter monsoon and its relation to the summer monsoon. *Adv. Atmos. Sci.*, **17**, 48–60.

——, Gu Lei, Wei Ke, et al., 2008: Studies of the dynamic processes of East Asian monsoon system and the quasi-stationary planetary wave activities. *Chinese J. Atmos. Sci.*, **32**(4), 950–966. (in Chinese)

Deser, C., and J. M. Wallace, 1990: Large-scale atmospheric circulation features of warm and cold episodes in the tropical Pacific. *J. Climate*, **3**, 1254–1281.

Ding Yihui, 1990: A statistical study of winter monsoons in East Asia. *J. Trop. Meteor.*, **6**(2), 119–128. (in Chinese)

Feng, J., and J. P. Li, 2011: Influence of El Niño Modoki on spring rainfall over South China. *J. Geophys. Res.*, **116**, D13102.

Gao, H., and S. Yang, 2009: A severe drought event in northern China in winter 2008–2009 and the possible influences of La Niña and Tibetan Plateau. *J. Geophys. Res.*, **114**, D24104, doi: 10.1029/2009JD012430.

Gong Daoyi and Wang Shaowu, 1998: Impact of ENSO on the seasonal rainfall in China. *J. Natural Disasters*, **7**(4), 44–52. (in Chinese)

——, ——, and J. H. Zhu, 2001: East Asian winter monsoon and Arctic Oscillation. *Geophys. Res. Lett.*, **28**, 2073–2076.

Guo Qiyun, 1994: Relationship between the variations of East Asian winter monsoon and temperature anomalies in China. *J. Appl. Meteor. Sci.*, **5**(2), 218–225. (in Chinese)

He Xicheng, Ding Yihui, He Jinhai, et al., 2006: Analysis on anomalous precipitation in southern China during winter monsoons. *Acta Meteor. Sinica*, **21**(4), 385–396.

Hoerling, M. P., A. Kumar, and M. Zhong, 1997: El Niño, La Niña, and the nonlinearity of their teleconnections. *J. Climate*, **10**, 1769–1786.

Huang Ronghui, Gu Lei, Chen Jilong, et al., 2008: Recent progresses in studies of the temporal-spatial variations of the East Asian monsoon system and their impacts on climate anomalies in China. *Chinese J. Atmos. Sci.*, **32**(4), 691–719. (in Chinese)

Jhun, J. G., and E. J. Lee, 2004: A new East Asian winter monsoon index and associated characteristics of the winter monsoon. *J. Climate*, **17**, 711–726.

Kao, H. Y., and J. Y. Yu, 2009: Contrasting eastern-Pacific and central-Pacific types of ENSO. *J. Climate*, **22**, 615–632.

Klein, S. A., B. J. Soden., and N. C. Lau., 1999: Remote sea surface temperature variations during ENSO: Evidence for a tropical atmospheric bridge. *J. Climate*, **12**, 917–932.

Kug, J. S., F. F. Jin, and S. I. An, 2009: Two types of El Niño events: Cold tongue El Niño and warm pool El Niño. *J. Climate*, **22**, 1499–1515.

Lau, N. C., and M. J. Nath, 2000: Impact of ENSO on the variability of the Asian-Australian monsoons as simulated in GCM experiments. *J. Climate*, **13**, 4287–4309.

—–, and —–, 2003: Atmoshpere-ocean variations in the Indo-Pacific sector during ENSO episodes. *J. Climate*, **16**, 3–20.

Lee, T., and M. J. McPhaden, 2010: Increasing intensity of El Niño in the central equatorial Pacific. *Geophys. Res. Lett.*, **37**, L14603, doi: 10.1029/2010GL044007.

Li Chongyin, 1988: Frequent strong activities of East Asian trough and the occurrence of El Niño event. *Sci. China (Ser. B)*, **31**(6), 667–674. (in Chinese)

—–, 1989: El Niño and warm winters in eastern China. *Chin. Sci. Bull.*, **34**(4), 283–286. (in Chinese)

—–, 1990: Interaction between anomalous winter monsoon in East Asia and El Niño events. *Adv. Atmos. Sci.*, **7**, 36–46.

—–, Yang Hui, and Gu Wei, 2008: Cause of severe weather with cold air, freezing rain and snow over South China in January 2008. *Climatic Environ. Res.*, **13**(2), 113–122. (in Chinese)

Li Chun and Ma Hao, 2012: Relationship between ENSO and winter rainfall over Southeast China and its decadal variability. *Adv. Atmos. Sci.*, **29**(6), 1129–1141.

Liu Ge, Ji Liren, Sun Shuqing, et al., 2012: Low- and mid-high latitude components of the East Asian winter monsoon and their reflecting variations in winter climate over eastern China. *Atmos. Oceanic Sci. Lett.*, **5**, 195–200.

Mao Rui, Gong Daoyi, and Fang Qiaomin, 2007: Influences of the East Asian jet stream on winter climate in China. *J. Appl. Meteor. Sci.*, **18**(2), 137–146. (in Chinese)

Mu Mingquan and Li Chongyin, 1999: ENSO signals in the interannual variability of East Asian winter monsoon. Part I: Observed data analyses. *Chinese J. Atmos. Sci.*, **23**(3), 276–285. (in Chinese)

Shao Xie, Zhang Zuqiang, and Tao Li, 2011: Influence analysis of quasi-biweekly oscillation during the low temperature, rain and snow weather in South China in 2007/2008 winter. *Meteor. Environ. Sci.*, **34**(3), 1–6. (in Chinese)

Song Lianchun, 2012: *Yearbook of Chinese Meteorological Disasters*. China Meteorological Press, Beijing, 5–7. (in Chinese)

Sun Bomin and Li Chongyin, 1997: Relationship between the disturbances of East Asian trough and tropical convective activities in boreal winter. *Chinese Sci. Bull.*, **42**(5), 500–504. (in Chinese)

Tao Shiyan, 1957: A synoptic and aerological study on a cold wave in the Far East during the period of the breakdown of the blocking situation over Eurasia and Atlantic. *Acta Meteor. Sinica*, **28**(1), 63–74. (in Chinese)

—– and Zhang Qingyun, 1998: Response of the Asian winter and summer monsoon to ENSO events. *Chinese J. Atmos. Sci.*, **22**(4), 399–407. (in Chinese)

Wang, B., and Q. Zhang, 2002: Pacific–East Asian teleconnection. Part II: How the Philippine Sea anomalous anticyclone is established during El Niño development? *J. Climate*, **15**, 3252–3265.

—–, R. G. Wu, and X. Fu, 2000: Pacific-East Asian teleconnection: How does ENSO affect East Asian climate? *J. Climate*, **13**, 1517–1536.

—–, J. Yang, T. J. Zhou, et al., 2008: Interdecadal changes in the major modes of Asian-Australian monsoon variability: Strengthening relationship with ENSO since the late 1970s. *J. Climate*, **21**, 1771–1789.

Wang Lin and Chen Wen, 2010: How well do existing indices measure the strength of the East Asian winter monsoon? *Adv. Atmos. Sci.*, **27**, 855–870.

—— and Feng Juan, 2011: Two major modes of the wintertime precipitation over China. *Chinese J. Atmos. Sci.*, **35**(6), 1105–1116. (in Chinese)

Wang Xin, Wang Dongxiao, Zhou Wen, et al., 2012: Interdecadal modulation of the influence of La Niña events on Meiyu rainfall over the Yangtze River valley. *Adv. Atmos. Sci.*, **29**, 157–168.

Wang Yun, Zhang Qingyun, and Peng Jingbei, 2008: Relationship between the intraseasonal oscillation of East Asian monsoon circulation and the heavy snow over southern China in boreal winter of 2007/2008. *Climatic Environ. Res.*, **13**(4), 459–467. (in Chinese)

Wang Zunya, Zhang Qiang, Chen Yu, et al., 2008: Characters of meteorological disasters caused by the extreme synoptic process in early 2008 over China. *Adv. Climate Change Res.*, **4**(2), 63–67. (in Chinese)

Webster, P., and S. Yang, 1992: Monsoon and ENSO: Selectively interactive systems. *Quart. J. Roy. Meteor. Soc.*, **118**, 877–926.

Wen, M., S. Yang, A. Kumar, et al., 2009: An analysis of the large-scale climate anomalies associated with the snowstorms affecting China in January 2008. *Mon. Wea. Rev.*, **137**, 1111–1131.

Wu, B., T. Li, and T. J. Zhou, 2010: Asymmetry of atmospheric circulation anomalies over the western North Pacific between El Niño and La Niña. *J. Climate*, **15**, 4807–4822.

Wu Bingyi and Huang Ronghui, 1999: Effects of the extremes in the North Atlantic Oscillation on East Asian winter monsoon. *Chinese J. Atmos. Sci.*, **23**(6), 641–651. (in Chinese)

——, Su Jingzhi, and Zhang Renhe, 2011: Effects of autumn-winter Arctic sea ice on winter Siberian high. *Chinese Sci. Bull.*, **56**(30), 3220–3228.

Wu, R. G., Z. Z. Hu, and B. P. Kirtman, 2003: Evolution of ENSO-related rainfall anomalies in East Asia. *J. Climate*, **16**, 3742–3758.

Xu Jianjun, and J. C. L. Chan, 2002: Interannual and interdecadal variability of winter precipitation over China in relation to global sea level pressure anomalies. *Adv. Atmos. Sci.*, **19**(5), 914–926.

——, Zhu Qiangen, and Zhou Tiehan, 1999: Sudden and periodic changes of East Asian winter monsoon in the past century. *J. Appl. Meteor. Sci.*, **10**(1), 1–8. (in Chinese)

Yang, S., K. M. Lau, and K. M. Kim, 2002: Variations of the East Asian jet stream and Asian-Pacific-American winter climate anomalies. *J. Climate*, **15**, 306–325.

——, Ding Xiaoli, Zheng Dawei, et al., 2007: Time-frequency characteristics of the relationships between tropical Indo-Pacific SSTs. *Adv. Atmos. Sci.*, **24**, 343–359.

Yeh, S. W., J. S. Kug, B. Dewitte, et al., 2009: El Niño in a changing climate. *Nature*, **461**, 511–514.

Yuan, Y., and S. Yang, 2012: Impacts of different types of El Niño on the East Asian climate: Focus on ENSO cycles. *J. Climate*, **25**(21), 7702–7722.

——, ——, and Z. Q. Zhang, 2012: Different evolutions of the Philippine Sea anticyclone between the eastern and central Pacific El Niño: Possible effects of Indian Ocean SST. *J. Climate*, **25**(22), 7867–7883.

—— and Yan Hongming, 2013: Different types of La Niña events and different responses of the tropical atmosphere. *Chinese Sci. Bull.*, **58**(3), 406–415.

Zhang, R. H., and A. Sumi, 2002: Moisture circulation over East Asia during El Niño episode in northern winter, spring and summer. *J. Meteor. Soc. Japan*, **80**, 213–227.

——, ——, and M. Kimoto, 1996: Impact of El Niño on the East Asian monsoon: A diagnostic study of the '86/87 and '91/92 events. *J. Meteor. Soc. Japan*, **74**, 49–62.

——, ——, and M. Kimoto, 1999: A diagnostic study of the impact of El Niño on the precipitation in China. *Adv. Atmos. Sci.*, **16**, 229–241.

Zhou, L. T., 2011: Impact of East Asian winter monsoon on rainfall over southeastern China and its dynamical process. *Int. J. Climatol.*, **31**, 677–686.

—— and R. G. Wu, 2010: Respective impacts of the East Asian winter monsoon and ENSO on winter rainfall in China. *J. Geophys. Res.*, **115**, D0217, doi: 10.1029/2009JD012502.

——, C.-Y. Tam, W. Zhou, et al., 2010: Influence of South China Sea SST and the ENSO on winter rainfall over South China. *Adv. Atmos. Sci.*, **27**(4), 832–844.

Zhu Yanfeng, 2008: An index of East Asian winter monsoon applied to description the Chinese mainland winter temperature changes. *Acta Meteor. Sinica*, **66**(5), 781–788. (in Chinese)

Zuo, Z. Y., S. Yang, W. Q. Wang, et al., 2011: Relationship between anomalies of Eurasian snow and southern China rainfall in winter. *Environ. Res. Lett.*, **6**(4), 045402, doi: 10.1088/1748-9326/6/4/045402.