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Impact of El Niño on atmospheric circulations over East Asia and rainfall in China: Role of the anomalous western North Pacific anticyclone

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Abstract This paper presents a review on the impact of El Niño on the interannual variability of atmospheric circulations over East Asia and rainfall in China through the anomalous anticyclone over western North Pacific (WNPAC). It explains the formation mechanisms of the WNPAC and physical processes by which the WNPAC affects the rainfall in China. During the mature phase of El Niño, the convective cooling anomalies over western tropical Pacific caused by the weakened convections trigger up an atmospheric Rossby wave response, resulting in the generation of the WNPAC. The WNPAC can persist from the winter when the El Niño is in its peak to subsequent summer, which is maintained by multiple factors including the sustained presence of convective cooling anomalies and the local air-sea interaction over western tropical Pacific, and the persistence of sea surface temperature anomalies (SSTA) in tropical Indian and tropical North Atlantic. The WNPAC can influence the atmospheric circulations over East Asia and rainfall in China not only simultaneously, but also in the subsequent summer after an El Niño year, leading to more rainfall over southern China. The current paper also points out that significant anomalies of atmospheric circulations over East Asia and rainfall over southern China occur in El Niño winter but not in La Niña winter, suggesting that El Niño and La Niña have an asymmetric effect. Other issues, including the impact of El Niño diversity and its impact as well as the relations of the factors affecting the persistence of the WNPAC with summer rainfall anomalies in China, are also discussed. At the end of this paper some issues calling for further investigation are discussed.

Keywords Atmospheric circulations over East Asia, Rainfall in China, El Niño, Anomalous western North Pacific anticyclone

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1. Introduction

In a mean climatological state, the western tropical Pacific is featured with the warmest sea surface temperature (SST) over a vast region known as the western Pacific warm pool. Meanwhile, there is a low SST zone that is a few degrees lower than that in western tropical Pacific warm pool, named as cold tongue, along the Peruvian and Ecuador coasts and a narrow zone near the equator in eastern equatorial Pacific. The east-west distribution of tropical Pacific SST has a significant interannual variability, manifested by the so-called El Niño or La Niña phenomenon. An El Niño exhibits strong warming of sea surface water in central and eastern equatorial Pacific, while a La Niña has an opposite pattern against El Niño featured with a drastic cooling-down of sea surface water in central and eastern equatorial Pacific. The SST anomalies (SSTA) associated with an El Niño or La Niña can be sustained for up to one year or so under a cycle about 2–7 years (Rasmusson and Carpente, 1982; Deser and Wallace, 1990).

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In addition, in the interannual timescale, the sea-level pressures over western and eastern tropical Pacific varies oppositely and like a seesaw, which is known as the Southern Oscillation (Walker and Bliss, 1930). The Southern Oscillation in the tropical atmosphere is intrinsically linked to the oceanic El Niño/La Niña phenomenon. They occur simultaneously and represent a differed manifestation of the same phenomenon in two media of ocean and atmosphere, and therefore, collectively are referred to as El Niño/ Southern Oscillation (ENSO) (Philander, 1983).

ENSO is the strongest signal in the interannual climate variability. Observations and numerical simulations have indicated that the ENSO, though a tropical phenomenon, can cause severe climate anomalies in many parts of the world, including China, resulting in meteorological disasters such as severe drought, flood and abnormal high/low temperature events, and affecting industrial, agricultural productive activities and people's daily life (Wallace and Gutzler, 1981; Shukla and Wallace, 1983; Lau, 1985; Philander, 1990; Wang et al., 1999; Huang et al., 2000, 2004; Zhang and Li, 2004). Understanding the impact of ENSO on climate and associated physical mechanisms have long been a hot topic for both atmospheric and oceanographic studies. The current paper, based on the research of the authors and other scholars, makes a review of the studies in the impact of El Niño on the interannual variability of atmospheric circulations over East Asia and rainfall in China. It demonstrates that the impact of El Niño is through the anomalous anticyclone over western North Pacific (WNPAC) and clarifies the generation and maintenance mechanisms of the WNPAC in association with an El Niño.

2. Simultaneous impact of El Niño

As early as in the 1970s, Chinese scholars started to study the impact of tropical Pacific SST on China's climate (Long Term Weather Forecast Group of the Institute of Geography of Chinese Academy of Science, 1977; Chen, 1977). They pointed out that the higher SST in central and eastern tropical Pacific is accompanied by a westbound stretch of the western North Pacific subtropical high, which then exerts effect on the rainfall in China. In an El Niño year, because of the lower SST over western Pacific, the number of typhoons generated in the region in both western Pacific and the South China Sea dwindle and the number of typhoons that land in China decline (Li, 1987, 1988). Huang and Wu (1989) found that the summertime convective anomalies near the Philippines associated with an El Niño can induce a quasi-stationary planetary wave that shapes up an East Asia/Pacific teleconnection, affecting the summer rainfall in China. They pointed out that the convective anomalies are related with the phase of El Niño. In the developing phase, the lower SST near the Philippines dampens the convective activities and induces a quasi-stationary planetary wave that leads to more summer rainfall in Yangtze-Huaihe River valley and less in Yellow River valley and northern China. In the decaying El Niño phase, higher SST is near the Philippines, along with rampant convective activities and a quasi-stationary planetary wave that makes dryness in Yangtze-Huaihe River valley and wetness in Yellow River valley, northern China, and to the south of middle and lower reaches of Yangtze River.

In order to investigate how the East Asia's climate is affected by the eastern equatorial Pacific SSTA during an El Niño period, Zhang et al. (1996) diagnosed the anomalous features of East Asian climate during two El Niños occurred in 1986/1987 and 1991/1992, respectively. They found an anomalous anticyclone in lower troposphere over western North Pacific (i.e., the WNPAC) when an El Niño is in its mature phase, and proposed a new mechanism that an El Niño affects the East Asian monsoon through the WNPAC. They pointed out that in the El Niño mature phase, the zonal distribution of anomalous heating field over tropical Pacific shows a distinct dipole pattern: convective heating anomalies over central and eastern tropical Pacific, and noticeable convective cooling anomalies over western tropical Pacific. The western tropical Pacific convective cooling anomalies induce a Rossby wave response in tropical atmosphere, resulting in the generation of the WNPAC. The WNPAC is conducive to the southwesterly anomalies along the southeast coast of East Asia, leading to the enhancement of southwest monsoonal flow there in summer and the weakening of the East Asian winter monsoon in winter.

An El Niño can produce a significant impact on China's rainfall in each season through the WNPAC. In the autumn, winter and spring of an El Niño year, significant positive rainfall anomalies occur in southern China (Zhang et al., 1999). An analysis for the cause of positive rainfall anomalies in southern China (Zhang and Sumi, 2002) indicated that the anomalous water vapor transport associated with the WNPAC enhances the water vapor transport around China's southeastern coast. The water vapor converges in southern China, resulting in increased the atmospheric precipitable water and enhanced rainfall in the El Niño episode. Figure 1 shows a schematic diagram for the WNPAC in an El Niño episode, and associated rainfall anomalies in China in autumn, winter and spring, respectively.

In the summer of an El Niño year, the WNPAC leads to a westward stretch of the western North Pacific subtropical high (Zhang et al., 1999), which enhances the water vapor transport from tropical western Pacific to China through the southwestern flanks of the subtropical high across the South China Sea. Although the water vapor transport associated with the westward stretch of subtropical high is favorable for increasing the rainfall over the lower reaches of Yangtze

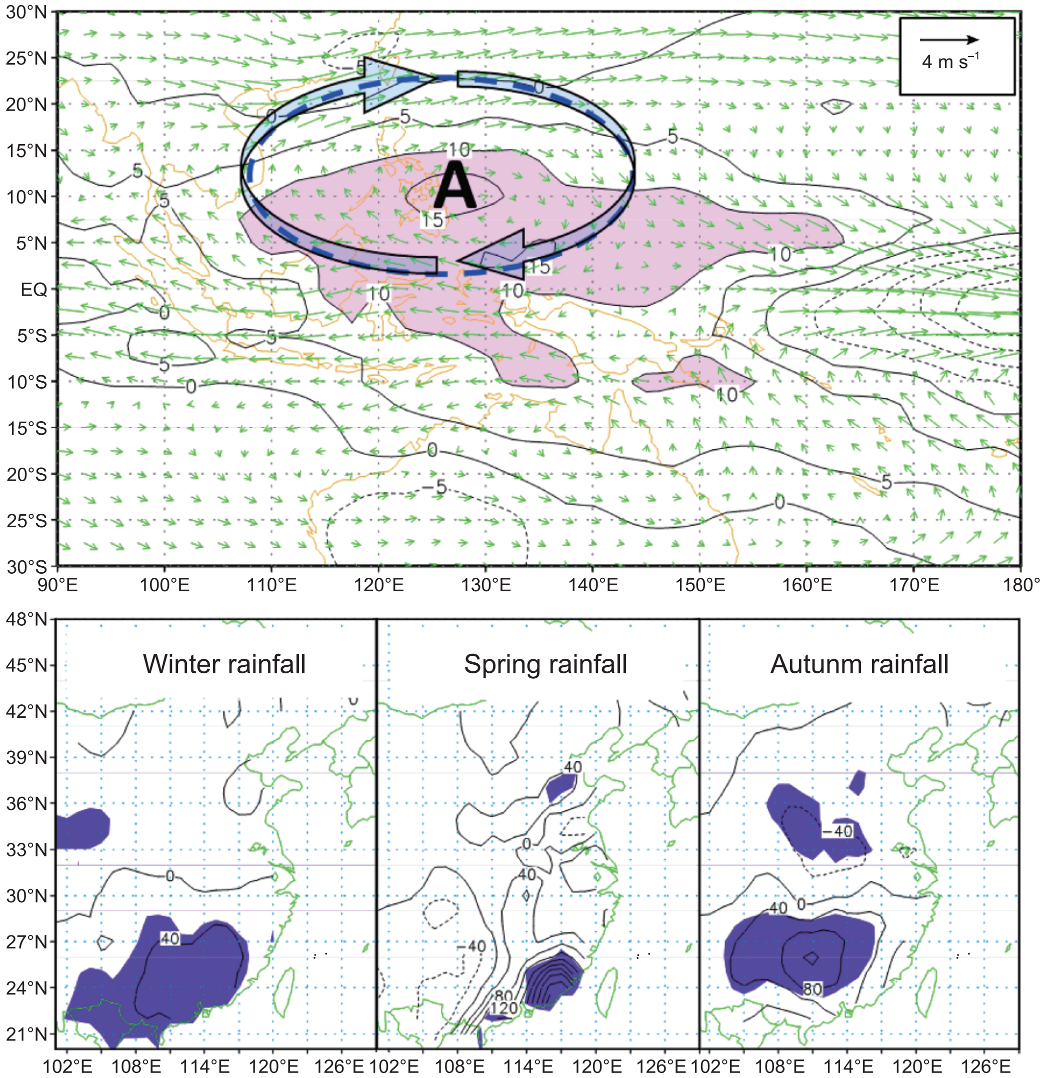

Figure 1 A schematic diagram for the WNPAC (upper panel, indicated by A) and rainfall anomalies in autumn, winter and spring (lower panel) during the El Niño mature phase. The contours in upper panel are anomalous outgoing longwave radiation (OLR) (units: W m^{-2}), arrows anomalous winds at 850 hPa (uniys: m s^{-1}), and shadings the areas of strongly weakened convection with anomalous OLR greater than 10 W m^{-2}. The contours in lower panel are composites of rainfall anomalies in the El Niño mature phase (units: mm) and shadings the areas with statistical significance exceeding the 0.05 level. See also Zhang and Sumi (2002).

River valley, the rainfall anomalies in the region are not statistically significant, whereas significant negative rainfall anomalies appear in northern China. The insignificant rainfall anomalies in the lower reaches of Yangtze River valley are related to the weakened Indian summer monsoon during the El Niño episode (Zhang et al., 1999). The water vapor transport from the Indian monsoon is out of phase with that from the southwestern flank of the western North Pacific subtropical high (Zhang, 2001). In the summer of an El Niño year, although the WNPAC enhances the water vapor transport and is favorable for increasing the rainfall over the middle and lower reaches of Yangtze River valley, the weakened Indian summer monsoon dampens the water vapor transport to China, offsetting the water vapor transport enhanced by the WNPAC and making the increased rainfall over the middle and lower reaches of Yangtze River valley insignificant. However, the declined water vapor transport from the Indian monsoon region results in significant negative anomalies of atmospheric precipitable water over northern China and hence a significant decrease of rainfall there (Zhang, 1999).

3. Lagged impact of El Niño

During an El Niño year, usually the eastern equatorial Pacific warms up in spring, and an El Niño shapes up in summer. The El Niño continues to develop afterwards till the peak is reached around the end of the year. After that, the SSTA weakens and tend to disappear in the following summer when only weak SSTA appears in eastern equatorial Pacific. In the research of the influence of El Niño on the East Asian monsoon, a key issue is how an El Niño peaked at the end of the year casts its lagged effect on the East Asian climate in the following summer. The WNPAC associated with an El Niño, proposed by Zhang et al. (1996), provides an idea for solving this question and promotes a range of studies working on the maintenance of the WNPAC and associated mechanisms.

Huang and Zhang (1997) first proposed the role played by the WNPAC in casting a lagged effect of El Niño on the East Asian climate in the following summer. They pointed out that during the decaying stage of an El Niño, the weakened western tropical Pacific convective activities can last through the following summer, encouraging anticyclonic anomalies over western tropical Pacific and South China Sea, and enhancing the southwest monsoonal flow over Yangtze-Huaihe River valley. Meanwhile, the propagation of quasi-stationary planetary waves can cause circulation anomalies over the middle and high latitudes of East Asian. Wang et al. (2000) proposed that the local sea-air interactions in western North Pacific region can allow the WNPAC appeared at the peak stage of an El Niño in winter to last to the following summer. In other words, the wind-evaporation-SST (WES) mechanism sustains the cold western North Pacific and the WNPAC, imposing a lagged El Niño effect on the East Asian summer climate in the following year.

Statistically, the SSTA in tropical Indian Ocean lags behind that in eastern equatorial Pacific by some 6 months (Tan et al., 2004). Therefore, in the subsequent summer after a peaked El Niño around the end of the year, the SSTA in tropical Indian Ocean reaches its peak (Du et al., 2009). The warming in tropical Indian Ocean in the following summer of an El Niño year may lead to the appearance of the WNPAC by affecting the Walker circulation (Annamalai et al., 2005; Yuan et al., 2008). Xie et al. (2009) pointed out that in the subsequent summer of a peaked El Niño, the positive tropical Indian Ocean SSTA can trigger up Kelvin waves in equatorial atmosphere, and induce the Ekman divergence mechanism over western North Pacific, causing the WNPAC. Rong et al. (2010) further suggested that the tropical North Atlantic SSTA associated with an El Niño should be conducive to the maintenance of the WNPAC. They pointed out that the tropical North Atlantic SST shows a significant increase in both the following spring and summer after a peaked El Niño in winter. The Gill-type atmospheric response to the warming in tropical North Atlantic allows the easterly anomalies associated with the equatorial Kelvin waves to stretch from western Indian Ocean to western Pacific. The easterly anomalies dampen convective activities through the divergence caused by the Ekman pumping effect, encouraging the formation of the WNPAC, which suggests that the North Atlantic SSTA in summer associated with El Niño may also play an important role in the relation of El Niño to the East Asian summer monsoon.

Figure 2 shows a schematic diagram for the mechanisms mentioned above, which lead to the WNPAC lasting through the following summer after a peaked El Niño in winter. The mechanisms include the sustained weakening of convective activities over western tropical Pacific (Huang and Zhang, 1997), the interactions between the cold SST and NWPAC in western tropical Pacific (Wang et al., 2000), the eastward equatorial Kelvin waves induced by the warm SSTs in tropical Indian Ocean (Xie et al., 2009) and in North Atlantic (Rong et al., 2010) appeared in the following summer after a peaked El Niño in winter. The NWPAC that sustained through the following summer may increase the summer rainfall in the middle and lower reaches of Yangtze River valley, and also acts as a bridge in connection of the East Asian winter monsoon with the East Asian summer monsoon (Chen et al., 2013).

4. Asymmetric impact of El Niño and La Niña

The distribution patterns of tropical Pacific SSTA in El Niño and La Niña are roughly opposite. However, the East Asian monsoon in El Niño and La Niña does not show opposite anomalies accordingly. The East Asian winter monsoon is significantly weakened in an El Niño year but not significantly enhanced in a La Niña year (Ni et al., 1995). The El

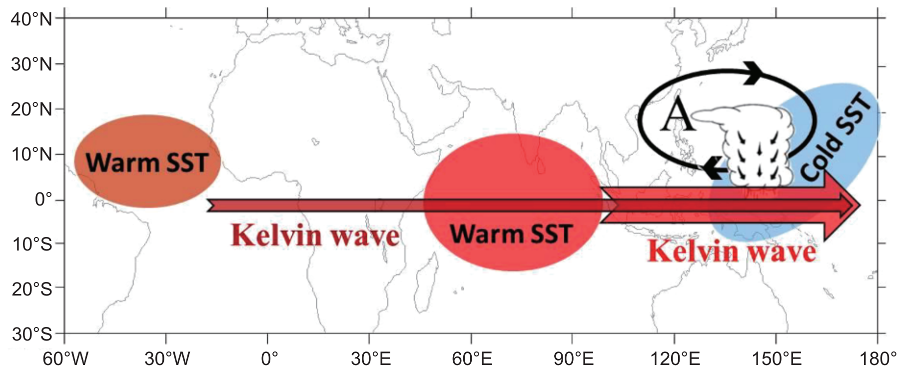

Figure 2 A schematic diagram for the WNPAC (indicated by A) and its formation mechanisms in the following summer after a peaked El Niño in winter (see text for the explanation).

Niño's impact on the East Asian monsoon is statistically significant, but insignificant in the case of La Niña (Zhang et al., 1996). Chen (2002) pointed out that La Niña has less influence on the East Asian winter monsoon compared with El Niño. These studies indicated that El Niño and La Niña have an asymmetric effect on the East Asian winter monsoon. The opposite distributions of SSTA in tropical pacific in El Niño and La Niña may not result in opposite anomalies of East Asian winter monsoon.

Zhang et al. (2015) and Li et al. (2015) analyzed the difference in the impacts of El Niño and La Niña on atmospheric circulations over East Asian and rainfall in southern China in the winter half year (November–April). They found that, as a Rossby wave response to the convective cooling anomalies over tropical western Pacific, a significant WNPAC appears in the El Niño winter half year. The WNPAC significantly enhances the water vapor transport to southern China, and positive anomalies of water vapor convergence result in the increased atmospheric precipitable water and specific humidity in the southeastern coast and the southern part of China, causing a significant increase of rainfall there. In the La Niña winter half year, although the convective heating anomalies over western tropical Pacific induce an anomalous cyclone over western North Pacific as a Rossby wave atmospheric response, the anomalous cyclone is much weak. The weak cyclone cannot reduce significantly the water vapor transported to southern China from the south, resulting in weak negative anomalies of water vapor divergence, atmospheric precipitable water and specific humidity, and thus insignificant negative anomalies of rainfall in southern China. Here we can see that the asymmetry of anomalous anticyclone and cyclone over western North Pacific in El Niño and La Niña winter half years results in the asymmetry of rainfall in southern China in responses to El Niño and La Niña.

For the physical mechanism of the asymmetric responses of the atmospheric circulations over western North Pacific to El Niño and La Niña, Wu et al. (2010) pointed out that the strong and weak amplitude of SSTA in tropical western Pacific in El Niño and La Niña lead to the strong anomalous anticyclone and weak anomalous cyclone, respectively. However, the results of Zhang et al. (2015) and Li et al. (2015) show that the amplitude of SSTA in tropical western Pacific in the El Niño winter half year may not be larger but even smaller than that in the La Niña winter half year. By taking the influence of the intraseasonal oscillation on the interannual variations into account, Zhang et al. (2015) and Li et al. (2015) proposed a physical mechanism explaining the asymmetric responses of atmospheric circulations over western North Pacific to El Nino and La Niña.

Figure 3 shows the variance of outgoing longwave radiation (OLR) and the 850 hPa kinetic energy over western tropical Pacific at the interannual and intraseasonal timescales in El Niño and La Niña winter half year, respectively. It can be seen that, for both OLR variance and kinetic energy, the interannual variations are much stronger than intraseasonal variation in El Niño winter half year, but a reversal appears in La Niña winter half year. In El Niño winter half year, the negative SSTA in western tropical Pacific dampens the updraft branch of the Walker circulation and suppresses convective activities, leading to a weak atmospheric intraseasonal oscillation but a stronger interannual variation. Consequentially, there appears a significant WNPAC in association with the interannual variation of El Niño. However, in La Niña winter half year, the positive SSTA in western tropical Pacific encourages the updraft branch of the Walker circulation and significantly enhances convective activities and atmospheric intraseasonal oscillation. As a result, the atmospheric variation at intraseasonal timescale becomes much stronger than that in interannual timescale. The atmosphere over western North Pacific varies mainly in intraseasonal timescale rather than interannual timescale, leading to a weak anomalous cyclone in association with the interannual variation of La Niña.

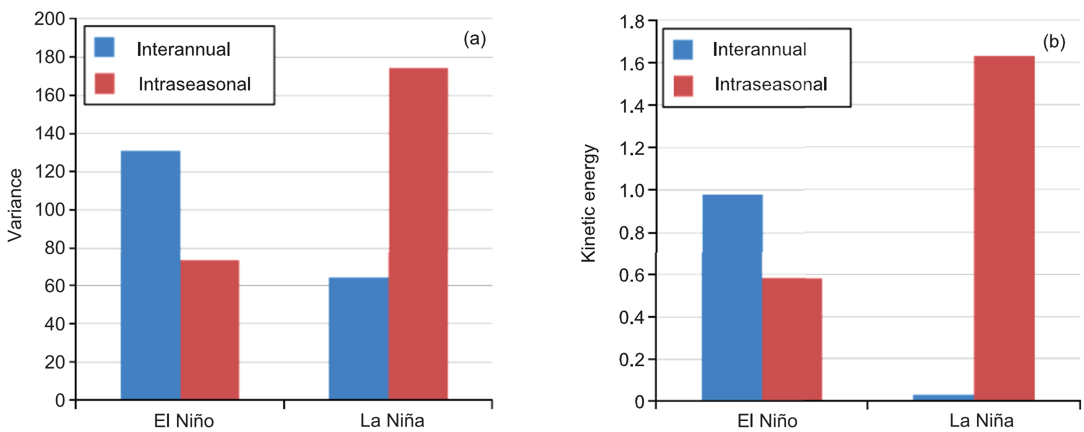

Figure 3 (a) OLR variance (units: $W^2 m^{-4}$) and (b) 850 hPa kinetic energy (units: $m^2 s^{-2}$) averaged over tropical western Pacific (110°–140°E, 0–17.5°N) for interannual (blue bars) and intraseasonal (red bars) timescales in El Niño and La Niña winter half years (November–April). The interannual and intraseasonal variations are obtained by the bandpass filters of 2–7 years and 10–50 days, respectively. The data used are from 1979 to 2010. Also see Zhang et al. (2015).

5. Discussions on El Niño diversity and lagged impact of El Niño

5.1 El Niño diversity and its impact

Some studies proposed that the El Niño can be divided into two types: eastern Pacific El Niño (EP-El Niño) and central Pacific El Niño (CP-El Niño), which correspond to warm SSTA in eastern and central equatorial Pacific, respectively (Larkin and Harrison, 2005; Ashok et al., 2007; Kug et al., 2009). How to classify an El Niño and how many groups of El Niño can fall into remain a matter of debate. Chen et al. (2015) divided El Niños into three types: warming SST in South American coast, around dateline, and in central-eastern equatorial Pacific. Wang and Wang (2013) sub-grouped the CP-El Niño into two types based on the warming sources either in central equatorial Pacific or in northeastern subtropical Pacific. As a matter of fact, El Niños are actually diversified in both spatial and temporal variations. Historically, there have been no two El Niños that are exactly the same. In fact, some studies raised doubts about the rationality of El Niño classification (Takahashi et al., 2011; Karnauskas, 2013). In addition, based on the El Niño observations to make classification statistically, the classification results depend largely on the standards and thresholds which are chosen, indicating that different standards and thresholds can produce different classification results.

El Niño's impact on the atmosphere is related to the distribution of SSTA. Different SSTA distributions can produce differed effects on the atmosphere. Tropical atmospheric motion is mainly direct atmospheric circulations driven by external forcing. Anomalous heating in the region of positive SSTA will lead to an anomalous ascending motion, while anomalous cooling in the region of negative SSTA to an anomalous descending motion. It is, therefore, easy to understand why an El Niño with warm SST in the eastern or central equatorial Pacific has differed impacts on the tropical atmosphere and on the East Asian or China's climate (Weng et al., 2007; Feng et al., 2010, 2011; Feng and Li, 2011; Zhang et al., 2011; Yuan and Yang, 2012; Yuan et al., 2012; Su et al., 2013; Wang and Wang, 2013). Factually, even for a single El Niño, the shift of the warm center during the El Niño episode can induce different atmospheric responses at its different evolution phases. In this context, the selection of a given tropical oceanic region to define an El Niño determines to a large extent the impact of El Niño. At present, there exist a number of El Niño indexes built on the SSTA in different equatorial Pacific regions (Li and Zhai, 2000). The application of El Niño index in different equatorial Pacific regions will undoubtedly generate different El Niño impacts on East Asian or China's climate.

By choosing the SSTA at NINO3 region (90°–150°W, 5°S–5°N) in eastern equatorial Pacific as an index of El Niño, Zhang et al. (1996, 1999) and Zhang and Sumi (2002) obtained significant anomalies features of atmospheric circulations over East Asia and rainfall in China in El Niño mature phase, and revealed the physical process that the El Niño affects East Asian monsoon through the WNPAC. A significant impact on atmospheric circulations over East Asia and rainfall in China by El Niño in its mature phase defined by the NINO3 index can be easily understood physically. The El Niño mature phase denoted by the NINO3 index corresponds to the most pronounced negative SSTA and the strongest convective cooling anomalies in western tropical Pacific during an El Niño episode. In this context, only the strongest anomalous signal in association with an El Niño appeared in western tropical Pacific can have a significant impact on the giant East Asian monsoon system. It can be seen from this perspective that the El Niño's impact on the East Asian climate is achieved through the convective cooling over western tropical Pacific, where the strongest convective cooling anomalies occur in the mature El Niño phase characterized by the NINO3 index. The selection of NINO3 SSTA as an El Niño index, therefore, can rationally characterize the El Niño's impact on East Asian and China's climate through the WNPAC.

5.2 Lagged El Niño effect factors and summer rainfall in China

As mentioned in Section 3, there are a number of factors that sustain the NWPAC throughout the following summer after an peaked El Niño in winter. To understand relations of these factors in summer to China's summer rainfall, correlation analyses are made between these factors in summer and summer rainfall in China. These factors include the summer SSTA in tropical Indian Ocean averaged at the area 20°S–20°N, 40°–100°E defined by Xie et al. (2009), and that in tropical North Atlantic averaged over 0°–20°N, 80°–30°W by Rong et al. (2010), and the summer sea-level air pressure anomalies averaged over 10°–20°N, 120°–150°E in the Philippine Sea, which characterizes the WNPAC by Wang et al. (2000). Figure 4 depicts the distributions of correlation coefficients between summer rainfall in China and each of these factors.

As shown in Figure 4, obvious differences can be seen among the distributions of correlation coefficients of summer rainfall with tropical Indian Ocean SST defined by Xie et al. (2009), tropical North Atlantic SST defined by Rong et al. (2010) and the WNPAC defined by Wang et al. (2000). When the tropical Indian Ocean is warmed up in summer, positive rainfall anomalies only occur in a limited area confined to China's eastern coast around the lower reaches of Yangtze River valley, but extensive significant negative rainfall anomalies prevail in North China (Figure 4a). A positive SSTA in tropical North Atlantic corresponds to positive rainfall anom-

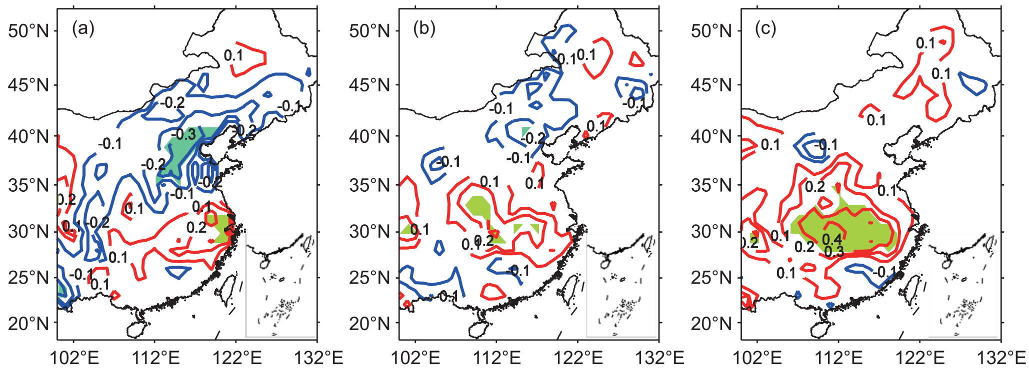

Figure 4 Correlation coefficients of summer rainfall to the east of 100°E in China with (a) SSTA in tropical Indian Ocean averaged over 20°S–20°N, 40°–100°E, (b) SSTA in tropical North Atlantic averaged over 0°–20°N, 80°–30°W, and (c) sea-level air pressure anomalies over the Philippines Sea averaged at the area 10°–20°N, 120°–150°E. Shadings are areas with statistical significance exceeding 0.05 level. The data of monthly rainfall, sea-level air pressure, and SST are from observations in 160 stations in China, NCEP/NCAR Reanalysis dataset, and HadISST dataset, respectively. The data period is from 1951 to 2015.

alies confined to the areas nearing the middle reaches of the Yangtze River valley (Figure 4b). When the summer sea-level air pressure anomalies in the Philippine Sea that characterize the NWPAC ascend, significant positive rainfall anomalies cover the entire middle and lower reaches of the Yangtze River valley except the area along the east coast (Figure 4c). Compared with the distributions of correlation coefficients of summer rainfall with tropical Indian Ocean and tropical North Atlantic SSTA, the correlation between summer sea-level air pressure in the Philippine Sea and summer rainfall in China is much stronger and the area with statistical significance is much larger.

As pointed out by Zhang (2001), the warm SST in tropical Indian Ocean in summer dampens the moisture transport from the Indian summer monsoon to eastern China, resulting in a significant decrease of rainfall in North China, while the anomalous water vapor transport associated with the western North Pacific subtropical high has a major impact on the rainfall over the middle and lower reaches of Yangtze River valley. In this context, the warming of the tropical Indian Ocean in summer in association with an El Niño may have an impact on China's summer rainfall mainly through affecting the water vapor transport stemmed from the Indian summer monsoon when significant negative rainfall anomalies appear in North China (Zhang, 1999). On the other hand, the sustained warming in tropical North Atlantic and the WNPAC in summer cast their impacts on China's summer rainfall mainly by affecting the western North Pacific subtropical high, when significant positive rainfall anomalies mainly exist in the middle and lower reaches of Yangtze River valley.

6. Conclusions and issues for further investigation

6.1 Conclusions

The El Niño has an important impact on atmospheric circulations over East Asia and rainfall in China. In the boreal spring, autumn and winter of El Niño mature phase, rainfall increases significantly in southern China, but in the summer of El Niño mature phase significant negative rainfall anomalies appear in northern China. The WNPAC associated with an El Niño is an important approach in the impact of El Niño on the East Asian monsoon and China's rainfall. The atmospheric Rossby wave response induced by the convective cooling anomalies over western tropical Pacific during an El Niño episode is the physical cause for the formation of WNPAC.

An El Niño peaked in winter has a lagged effect on atmospheric circulations over East Asia and rainfall in China in the following summer through the sustained WNPAC. The persistence of the WNPAC is under the effect of a number of factors, including the persistence of weakened convections over western tropical Pacific, the local air-sea interactions over western North Pacific, the warming of tropical Indian Ocean and tropical North Atlantic, These factors, associated with an El Niño, appear in the following summer after a peaked El Niño in winter.

El Niño and La Niña have a noticeably asymmetric effect on wintertime East Asian atmospheric circulations and China's rainfall. In an El Niño winter, the convections over tropical western Pacific are suppressed, which restrain the intraseasonal oscillation, and the interannual variations are dominant. The WNPAC in association with the interannual variation of El Niño are statistically significant, resulting in more rainfall in southern China. In a La Niña winter the rampant convective activities appear over western tropical Pacific and the intraseasonal variation is statistically significant and dominant. The weak interannual variation in association with La Niña leads to insignificant atmospheric circulations over East Asian and rainfall in China.

6.2 Issues for further investigation

This paper makes an overview of the previous studies about the effect of El Niño on atmospheric circulations over East Asia and rainfall in China through the WNPAC and associated physical processes. However, there are still a range of issues in this research field that need for further investigation. The specific issues are listed as follows.

(1) In this paper it is demonstrated that a number of factors in association with El Niño can affect the maintenance of the WNPAC, and these factors may have different relations with the summer rainfall in China (Figure 4). However, it remains unclear about the relative importance and difference of those individual factors in maintaining the WNPAC and affecting the summertime atmospheric circulations over East Asia and rainfall in China. A deepened study of the issue is helpful in enhancing the understanding and predicting of lagged impact of El Niño on East Asian summer climate and China's summer rainfall.

(2) Considering the El Niño diversity, the results in the present paper is mainly valid for EP-El Niño. For the effect of CP-El Niño on atmospheric circulations over East Asia and China's climate, at present there are no consistent conclusions, even opposite results are obtained. Previous studies indicated that either a weak anomalous anticyclone (e.g., Feng et al., 2010; Su et al., 2013) or an anomalous cyclone (e.g., Zhang et al., 2011; Chen et al., 2014) could appear over western North Pacific corresponding to a CP-El Niño. Such difference may arise from the difference in SSTA positions associated with a CP-El Niño. In this context, it is necessary to deepen the study in selecting or setting up an El Niño index that can characterize the impact of El Niño on East Asian climate, which is a key and basic topic for understanding and predicting El Niño's impact on East Asian monsoon.

(3) Because in general the peak of an El Niño occurs in winter and a weak SSTA in central and eastern equatorial Pacific appears in summer, numerous studies have been made to focus on El Niño's lagged effects on East Asian summer climate. As a matter of fact, in central and eastern equatorial Pacific strong positive SSTA can also appear in summer, an El Niño in summertime can produce a significant simultaneous impact on atmospheric circulations over East Asia and China's summer rainfall as well (Zhang et al., 1996, 1999; Zhang, 1999). However, it remains unclear about the relative role played by the simultaneous and lagged effect of El Niños, which is needed for further investigation.

(4) In addition to El Niño, previous studies have shown that the atmospheric circulations over East Asia and rainfall in China can be also affected significantly by a range of other external factors, including the thermal anomalies over the Tibetan Plateau, thermal conditions over Eurasian continent, human activities, and so on (Huang et al., 2012; Zhang et al., 2013; Zhang, 2015a, 2015b; Wu et al., 2016). It is needed in the future study to clarify the relative importance of these external factors in shaping up the climate variability over East Asia and in China, compared with El Niño.

(5) Some studies indicated that there is decadal variability in the relationship between ENSO and East Asian summer monsoon (Wang, 2002); the correlation between tropical Indian Ocean SSTA and the WNPAC in summer got strengthened after the middle 1970s (Huang et al., 2010); and the Pacific Decadal Oscillation (PDO) can modulate the relationship between ENSO and East Asian winter monsoon (Chen et al., 2013). Therefore, the influence of global warming and decadal climate variability on the interannual relationship between East Asian monsoon and El Niño is also an important topic to be worked on in the future.

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