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Differences in spring precipitation over southern China associated with multiyear La Niña events

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Abstract

Composite analyses were performed in this study to reveal the difference in spring precipitation over southern China during multiyear La Niña events during 1901 to 2015. It was found that there is significantly below-normal precipitation during the first boreal spring, but above-normal precipitation during the second year. The difference in spring precipitation over southern China is correlative to the variation in western North Pacific anomalous cyclone (WNPC), which can in turn be attributed to the different sea surface temperature anomaly (SSTA) over the Tropical Pacific. The remote forcing of negative SSTA in the equatorial central and eastern Pacific and the local air-sea interaction in the western North Pacific are the usual causes of WNPC formation and maintenance. SSTA in the first spring is stronger than those in the second spring. As a result, the intensity of WNPC in the first year is stronger, which is more likely to reduce the moisture in southern China by changing the moisture transport, leading to prolonged precipitation deficits over southern China. However, the tropical SSTA signals in the second year are too weak to induce the formation and maintenance of WNPC and the below-normal precipitation over southern China. Thus, the variation in tropical SSTA signals between two consecutive springs during multiyear La Niña events leads to obvious differences in the spatial pattern of precipitation anomaly in southern China by causing the different WNPC response.

Key words: multiyear La Niña, precipitation anomaly, anomalous western North Pacific cyclone, southern China

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1 Introduction

The El Niño-Southern Oscillation (ENSO) phenomenon is a large-scale atmosphere-ocean interaction usually occurs in the tropical Pacific and has crucial effects on the global climate through atmospheric teleconnections (Bjerknes, 1969; Wallace et al., 1998; Wang and Picaut, 2004). ENSO is a key factor affecting interannual and seasonal climate variability in East Asia, such as air temperature and precipitation in every season (Zhang et al., 1996, 1999; Chen et al., 2000; Wang et al., 2000; Wu et al., 2003; Li and Ma, 2012; Liu et al., 2022).

The key system that transmits tropical ENSO signals to East Asia and has important effects on the climate of East Asia is an anomalous anticyclone/cyclone in the tropical western North Pacific (WNP), designated the western North Pacific anomalous cyclone (WNPAC)/WNPC (Zhang et al., 1996, 1999; Wang et al., 2000; Xie et al., 2016; Li et al., 2017; Wu et al., 2017a, b). Zhang et al. (1996) noted that the anomalous atmospheric circulation over the WNP is a response to suppressed convection caused by local sea surface temperature (SST) cooling. Wang et al. (2000) found that these WNP SST anomalies are induced by a low-level WNPAC, which is caused by equatorial central Pacific (CP) SST warming. WNPAC can be maintained by the air-sea interaction mechanism from winter to spring (Wang et al., 2000; Li et al., 2017). There are several other mechanisms proposed for the maintenance of the WNPC/WNPAC and follows are three main mechanisms: the Indo-Western Pacific Ocean capacitor (Xie et al., 2009, 2016), the C-mode (Stuecker et al., 2015; Zhang et al., 2016), and the moist enthalpy advection mechanism (Wu et al., 2017a, b).

In general, the WNPAC/WNPC begins to form in late autumn, fully established in peaking winter and can last into the following summer (Wang et al., 2000; Xie et al., 2009; Wu et al., 2017a, b). This long-standing abnormal circulation can continually affect the climate of China. Influenced by WNPAC, the anomalous southwest winds transport moisture from the South China Sea into southern China, causing above-normal precipitation over

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southern China in the mature phase (Zhang and Sumi, 2002). The effects on southern China from ENSO can last into the following spring. For example, there is above-normal precipitation in southern China in spring during El Niño years (Zhang et al., 1999). Roughly opposite to the El Niño situation, there is drought in southern China due to the effects of WNPC during La Niña events (Zhang et al., 1996; Zhang and Sumi, 2002; Wang et al., 2017). Persistent drought from winter to spring can cause severe economic and social hardship in these regions (Sun and Yang, 2012). The study of spring rainfall variability in southern China is vital for reducing the related disaster.

Previous studies have found that there are many asymmetries in the occurrence mechanism and climate impacts between two opposite phases of ENSO (Hoerling et al., 1997; Kessler, 2002; Kug et al., 2005; McPhaden and Zhang, 2009; Ohba and Ueda, 2009; Okumura et al., 2011; Karori et al., 2013). Particularly in South China precipitation, there is statistically above-normal precipitation during the wintertime of El Niño, but the relationship between precipitation and La Niña weakens, for the reason of the asymmetric effects of ENSO on anomalous atmospheric circulation in the WNP (Zhang et al., 1996, 2015, 2017; Wu et al., 2010; Li et al., 2015). As pointed out by Wu et al. (2010), the amplitude of SST anomalies in the tropical western Pacific is small (large) during La Niña (El Niño) events, causing weak (strong) WNPAC (WNPC). Zhang et al. (2015) and Li et al. (2015) found that the increased convection and significant intra-seasonal variability in the WNP weaken the relationship between precipitation in southern China and La Niña events, but interannual variability dominates in the WNP due to suppressed convection and inapparent intra-seasonal oscillations during El Niño years. It is necessary to study the two phases of ENSO separately and not simply to consider them as two opposite phases. From the perspective of time evolution, after El Niño reaches its mature phase, it tends to decay and die out rapidly in the next summer, whereas La Niña is often sustained and strengthens again in the next winter, developing into another event, called a multiyear La Niña or double-dip La Niña (Hu et al., 2014; Zhang and Guo, 2016; Zhang et al.,2022; DiNezio and Deser, 2014, 2017; Feng et al., 2015, 2020, 2021; Zheng et al., 2015; Luo et al., 2017; Gao et al., 2022a, 2022b).

The effects on climate variability are significantly different between the first and second years during multiyear La Niña events (Okumura et al., 2017; Raj Deepak et al., 2019; Iwakiri and Watanabe, 2020). China is significantly affected by the East Asian monsoon; thus, precipitation is typically low in winter and sometimes leads to droughts. A prolonged drought from winter to spring may have even larger impacts on economics and agriculture (Chen et al., 2014). For example, prolonged drought caused great damage to agriculture and society in southern China during the 2010/2011 La Niña event (Sun and Yang, 2012). Multiyear La Niña events account for around 50% of all events (Gao et al., 2022b), but their impacts on the climate of China are not well understood. Previous studies on the ENSO influence on the climate over China have mostly focused on the influence of a single event and divided multiyear La Niña events into several independent La Niña events. However, the effects of two consecutive years of La Niña events on climate may not be the same. Therefore, the two consecutive years of La Niña events should be considered as one event (as a multiyear La Niña) to study the different impacts on the climate of China between the first and the second year. A systematic study of the different influences and mechanisms between two consecutive years of a multiyear La Niña event on the climate of China will help to improve the predictability of seasonal and interannual climates in China.

In this study, we evaluate the impacts of multiyear La Niña on precipitation over China during the first and second boreal spring, using observational and reanalysis data sets. The data and methodology are introduced in Section 2. Section 3 describes the results from observational analysis of multiyear La Niña events. Summaries and discussions are presented in Section 4.

2 Data and methods

2.1 *Observational data*

In this study, we used monthly SST from the Hadley Centre Sea Ice and SST (HadISST) dataset (Rayner et al., 2003) for 1901–2020 and land precipitation from the Global Precipitation Climatology Centre (GPCC) version 2022 (Schneider et al., 2022) for 1891–2020. In addition, monthly sea level pressure (SLP), wind, precipitation, geopotential height, and specific humidity were adopted from NOAA-CIRES-DOE Twentieth Century Reanalysis (20CR) version 3 (Slivinski et al., 2019) for 1836–2015. The spatial resolution of the above data is on a 1° grid.

To detect the influence and possible mechanism of a multiyear La Niña on precipitation over China, we performed a composite analysis of seasonal SST, precipitation, moisture transport, SLP, and general circulation anomalies for the common period. Before the composite analysis, the linear trends of monthly anomalies of these datasets were removed for 1901–2015 at each grid point. Statistical significance of the composite anomalies is assessed utilizing the two-tailed student *t*-test. The decadal variability does not then have effects on the results of the following composite analysis. These anomalies were averaged over boreal winters (December-January-February) and boreal springs (March-April-May) to reduce disturbance related to subseasonal variability. Note that, unless otherwise specified, the seasons mentioned in this study refer to those in the Northern Hemisphere.

2.2 *Definition of multiyear La Niña*

We categorized these La Niña events based on a time series of monthly Niño3.4 index, averaged SST anomalies over the Niño3.4 region (5°S–5°N, 120°–170°W), from the HadISST dataset for 1901–2020. The criterion for distinguishing the type of La Niña event used follows Okumura et al. (2017). The year in which ENSO first developed is identified as year 0, and the subsequent year is year 1. When the Niño3.4 index is smaller than −0.75 standard deviations (SD, calculated for each month separately) in any month during wintertime (October-November-December-January-February, ONDJF) and remains smaller than −0.5 SD in any month during the following wintertime, a multiyear La Niña event is defined (Okumura et al., 2017). And a single-year La Niña event is defined when the Niño3.4 index is smaller than −0.75 SD in any month during ONDJF and turns to be larger than −0.5 SD in all months during the following ONDJF (Okumura et al., 2017). The long-term linear trend of the Niño3.4 index is removed, and a three-month running mean is applied before identifying La Niña events. Based on the above criterion, there are 10 multiyear La Niña events (1908, 1916, 1949, 1954, 1970, 1973, 1983, 1998, 2007, and 2010 are the first developing years of multiyear La Niña events), and 12 single-year La Niña events were identified (1903, 1922, 1924, 1933, 1938, 1942, 1947, 1964,

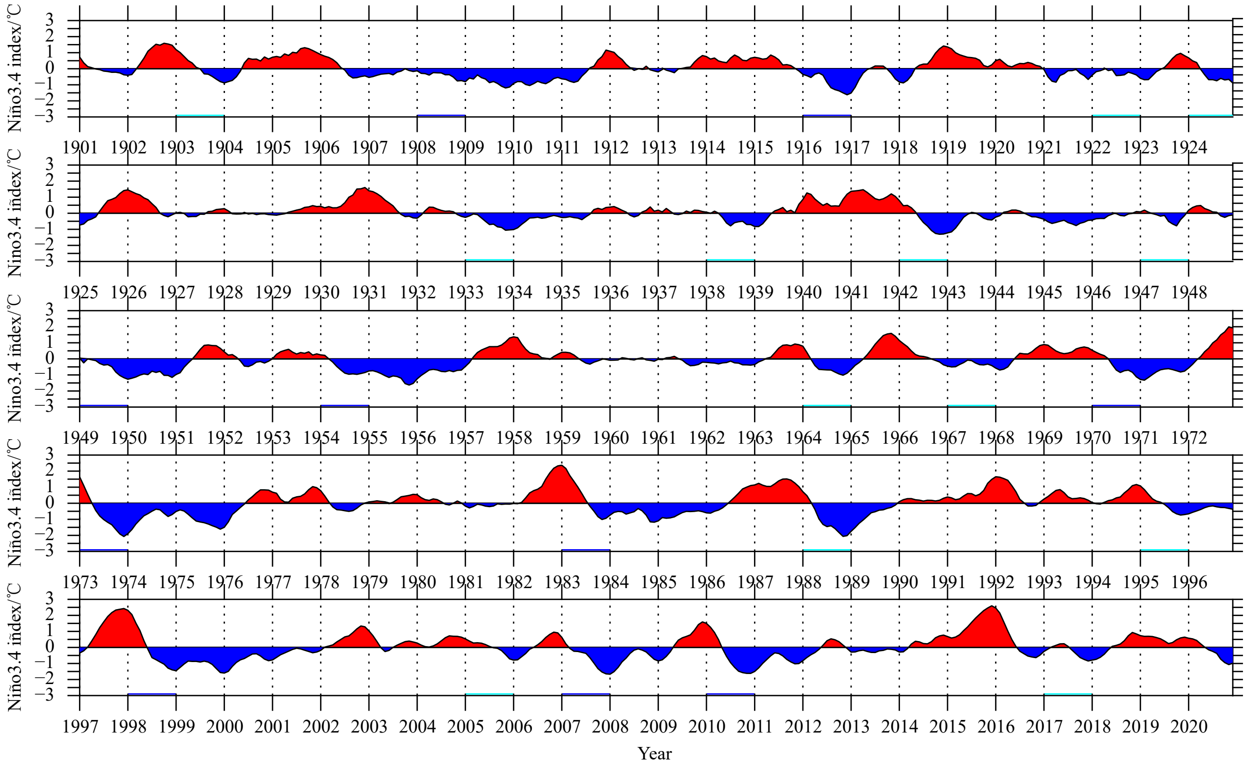

Fig. 1. The time evolution of the Niño3.4 index (℃) based on the HadISST dataset from 1901 to 2020. The year indicated by blue (light blue) bars at the bottom is the year 0 of the multi-year (single-year) La Niña event.

1967, 1988, 1995, and 2005 are the year 0 of single-year La Niña events). Although the periods are slightly different from those of Okumura et al. (2017) in this study, the events identified are the same (Fig. 1). In addition, the uncertainties of SST data, particularly before World War II, have impacts on Niño indices (Huang et al., 2013, 2016, 2020), which may influence the identification of multiyear (single-year) La Niña events.

Figure 2 shows the composite Niño3.4 index for these two types of La Niña events. The evolution is significantly different between multiyear and single-year La Niña events. During multiyear La Niña events, after the first valley in the boreal winter, the Niño3.4 index increases but remains negative in the following spring and summer and then develops into another La Niña phase (Fig. 2a). A single-year La Niña decays rapidly to a normal phase in the following spring then turn to be an El Niño event or still be a normal state in summer (Fig. 2b). Furthermore, for multiyear La Niña events, there are notable differences in the evolution between two consecutive years. First, the amplitude of anomalous SSTs in the first year is larger than that in the second year, although in both years, the peak occurs around December, which is consistent with conventional La Niña events. Second, the duration of SST cooling is longer due to larger SST anomalies in the first year (Hu et al., 2014), which could cause larger climate impacts on China. Coinciding with the amplitude of La Niña, anomalous SSTs in the equatorial Pacific rapidly decays to the normal phase in the second year. Based on these differences, the climate effects on China may be different between two consecutive years during multiyear La Niña events.

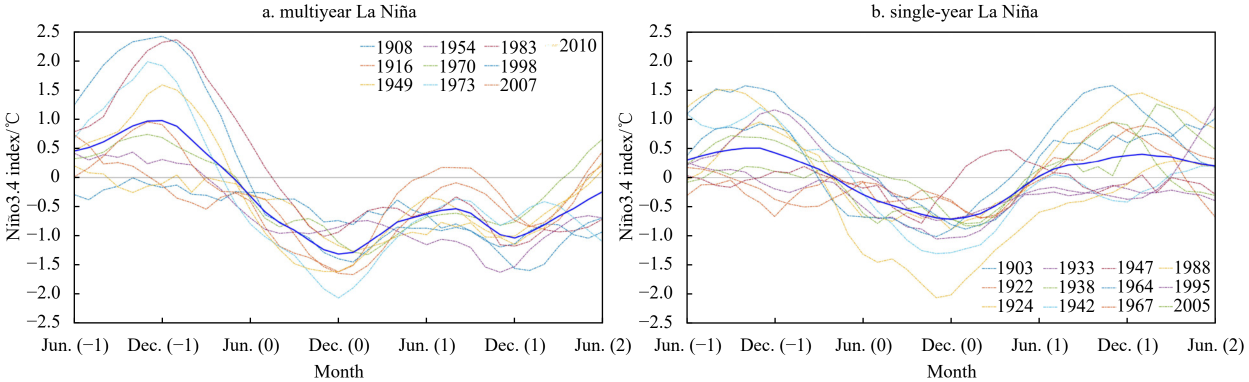

Fig. 2. Time series of the Niño3.4 index (℃) from Jun. (−1) to Jun. (2) for 10 multiyear La Niña events (a) and 12 single-year La Niña events (b). The solid blue line is the composite time series. The year that the first La Niña develop is regard as year 0. The following year is year 1 and so on.

3 Results

3.1 *Spatial pattern of anomalous precipitation*

Figure 3 shows the composite distribution of the anomalous precipitation over China in the first and second winters (Figs 3a and b) and springs (Figs 3c and d) from 1901 to 2015. The composite analysis reveals that the main patterns of precipitation anomalies are significantly distinct between the first and second springs but show little difference between the first and second winters. In winter, there is a precipitation deficit over southern China (20°–35°N, 105°–125°E) in both years (Figs 3a and b). In the first spring, there is below-normal precipitation over southern China, and the region of drought is the same as that in the first winter, but the magnitude is much larger than that in winter (Fig. 3c). Precipitation deficit in southern China and the middle and lower reaches of the Changjiang River (Yangtze River) are statistically significant (Fig. 3c). Compared with the first year, there are negative precipitation anomalies over southeast China but above-normal precipitation over other regions of southern China in the second spring (Fig. 3d). From the first to the second springs, considerable changes occur in precipitation anomalies, which are not found between the first and second winters. Although winter is usually the strongest season for tropical SST anomalies, the difference in anomalous precipitations between the

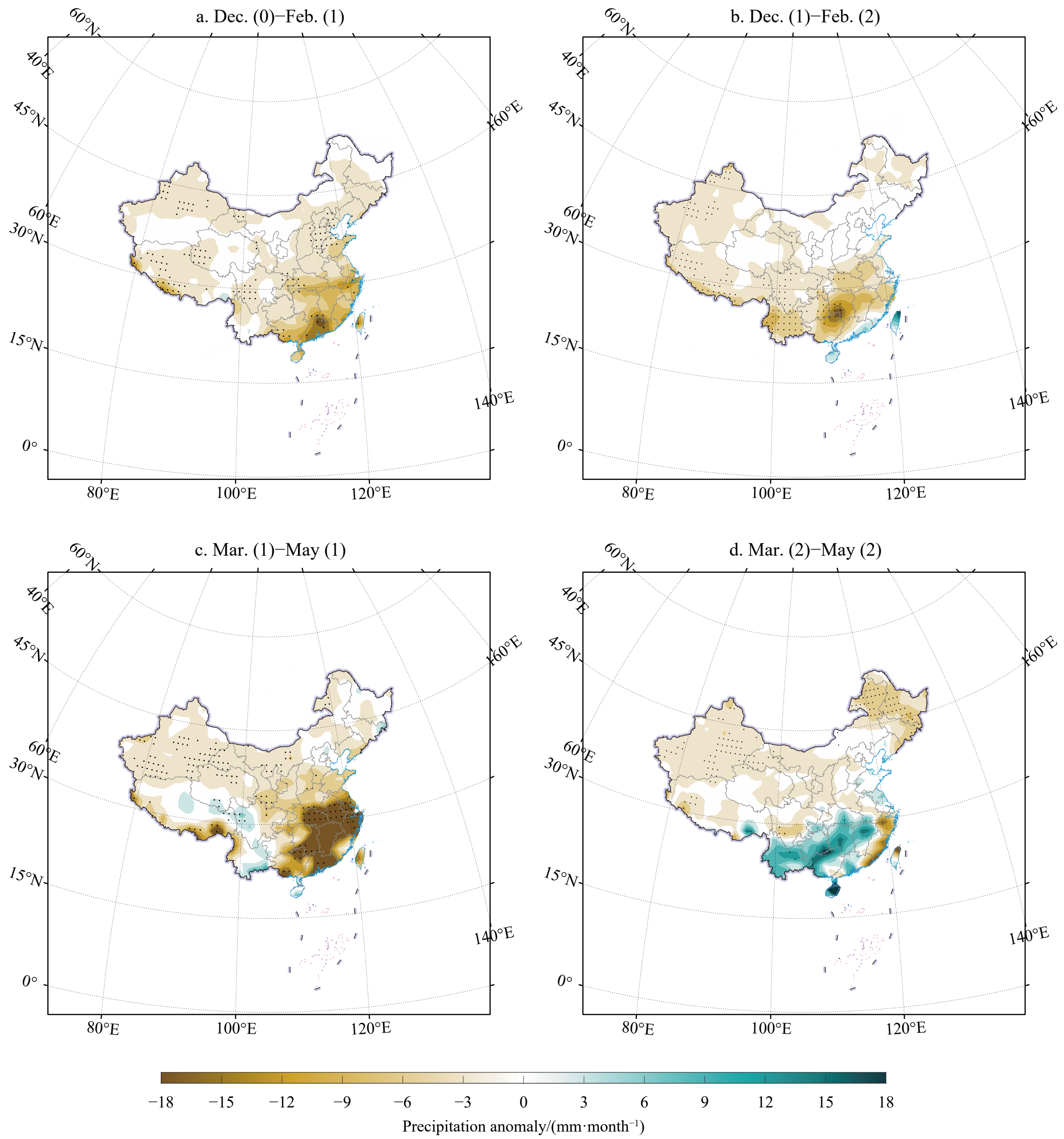

Fig. 3. Observed precipitation anomalies (mm/month) during winter (a and b) and spring (c and d) of composite multiyear La Niña events from 1901 to 2015. Black dots indicate the areas where precipitation anomalies are statistically significant above a 90% confidence level. The background map downloaded from http://211.159.153.75/browse.html?picId=%224o28b0625501ad13015501ad2bfc2188%22.

two winters over southern China is not apparent except for a slight difference in the magnitude. The precipitation anomalies over southern China show minor precipitation deficits in both the first and second winters, which is consistent with La Niña events typically causing winter precipitation deficit over southern China (Wang et al., 2000; Wang and Zhang, 2002; Zhang et al., 2015). Due to the great difference in southern China in spring, we focused on the analysis of these different anomalous spring precipitations during the multiyear La Niña events.

3.2 *Atmospheric circulation anomalies*

To understand why a multiyear La Niña brings such different precipitation anomalies to southern China in spring, we compared atmospheric circulation anomalies between the first and second springs. The composite analysis of SLP, 850 hPa horizontal winds and precipitation anomalies during the two springs is shown in Fig. 4. For the anomalous atmospheric circulation, there are both similarities and differences between the first and second spring. In both springs, the spatial distribution of anomalous winds is shown as easterly wind anomalies in the equatorial CP, westerly wind anomalies in the equatorial Indian Ocean (IO) and WNPC. The negative SLP anomaly and positive precipitation anomaly are associated with WNPC. However, the intensity of these anomalous atmospheric circulations in the second year is weaker than those in the first year. In addition, the meridional component of the WNPC almost disappears in the second year (Fig. 4b) and thus may have little influence on precipitation over southern China. Precipitation anomalies in the WNP also differ in intensity and extent. The positive precipitation anomalies in the WNP are more intense and more widespread in the first spring, suggesting stronger convection in the first spring, which is consistent with the stronger WNPC. In particular, the WNPC/WNPAC is the key link between ENSO and East Asian climate variability, and strongly influences climate variability in China. Although there is abnormal cyclonic circulation in the WNP in both the first and second springs, the intensity and range of the WNPC are remarkably different, which could have distinctly different impacts on the climate of China. During the first spring, the northeasterly wind anomalies located in the northwestern part of the WNPC dominate southern China (Fig. 4a). Unlike the first year, there are no significant anomalous northeasterly winds over southern China in the second spring (Fig. 4b). These different wind anomalies over southern China may have different impacts on precipitation anomalies. Thus, the anomalous precipitation differences over southern China between the first and second springs appear due to the differences in the atmospheric circulation anomalies in the WNP.

The anomalous precipitation affected by ENSO is mainly through low-level WNPC/WNPAC, which changes water vapor transport (Zhang et al., 1996). During multiyear La Niña events, the spatial pattern is distinct between the two springs, and the vertically integrated moisture (VIM) convergent in the Maritime Continent (MC) in the first spring (Fig. 5a) is consistent with above-normal precipitation in this region (Fig. 4a); however, these anomalies are weak and insignificant in the second year. Coincident with 850 hPa northeasterly wind anomalies, the VIM in southern China is divergent and transported into the South China Sea and Southeast Asia region (Fig. 5a). It is simultan-

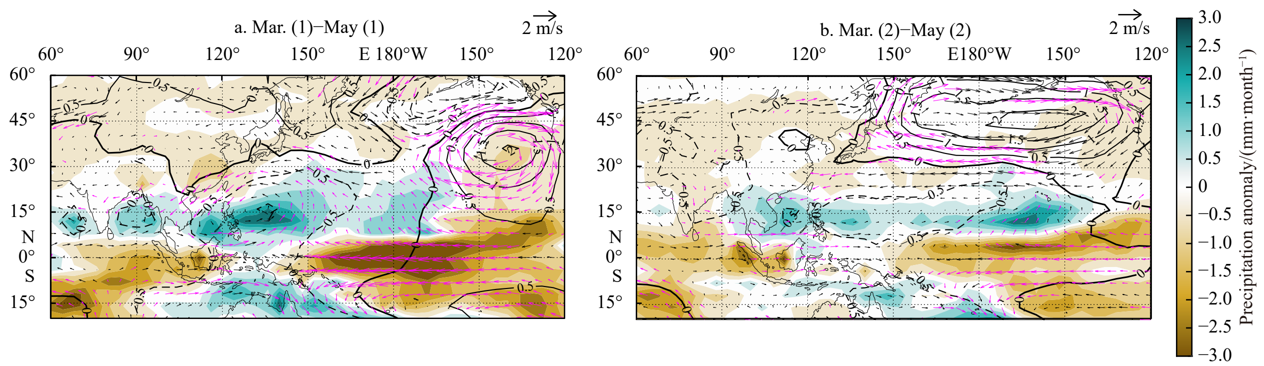

Fig. 4. Observed 850 hPa horizontal wind (vector, m/s), SLP (contours, hPa) and precipitation (shading, mm/month) anomalies of the 10 multiyear La Niña events. The wind anomalies at 90% confidence level are shown in purple.

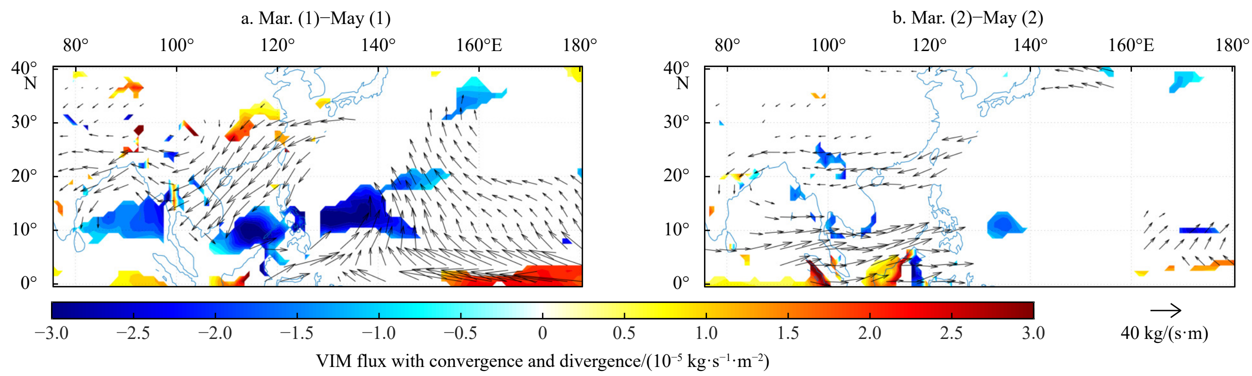

Fig. 5. Vertically integrated moisture (VIM) flux (vector; kg/(s · m)) with convergence and divergence (shading; 10^{-5} kg/(s · m^2)) above the 90% confidence level are shown.

eously accompanied by anomalous descent at 500 hPa over southern China (Fig. 6a). In addition, during the first spring, the abnormal moisture and vertical motion are consistent with the precipitation deficit over southern China. However, for anomalous vertical motion in the second spring, there was no abnormal subsidence but abnormal upward movement over southern China (Fig. 6b). The anomalous water vapor of the second year was transported westward to South China and the northern South China Sea (Fig. 5b). In contrast to the first spring, there is no significant water vapor divergence or convergence or meridional moisture transport over southern China in the second spring (Fig. 5b). Therefore, the precipitation in southern China does not decrease and may even increase the second spring (Fig. 3b). In summary, in the first year, the WNPC is more likely to produce lower moisture conditions in southern China, which results in below-normal precipitation. However, in the second year, the weak WNPC does not significantly affect the moisture in southern China.

3.3 *Possible mechanism for distinct anomalous precipitation pattern*

The SST anomalies in the WNP and equatorial CP are essential for WNPC/WNPAC in terms of formation and maintenance (Wang et al., 2000). First, SST cooling in the equatorial CP is associated with SST warming in the WNP. Then the increased SSTs in the WNP affect WNPC through Rossby wave response. To verify the mechanism for the different precipitation anomalies between two consecutive springs, we further investigated the composite monthly anomalous SST and 850 hPa wind in these two consecutive winters and springs (Fig. 7). The WNPC/WNPAC is generally established in the autumn of year 0, reaches its peak in the spring of the following year, and can be maintained until decaying in the summer (Wang et al., 2000; Zhang et al., 2017). The evolution of the WNPC in the first year develops in the fall (not shown) and peaks in the spring, which is consistent with the conventional ENSO pattern (Fig. 7c). In the second year, however, although WNPC development still starts in the fall, the WNPC signal is weak in the following spring. The WNPC/WNPAC in spring is mainly maintained by *in-situ* atmosphere-ocean interactions (Wang et al., 2000; Li et al., 2017). The different WNPCs in spring may be influenced by distinct tropical Pacific SST anomalies between two consecutive years. As shown in Fig. 7, the anomalous SSTs in the tropical Pacific in the second spring is weaker than that in the first spring. During the second spring, SST warming is weak in the WNP, and minor negative SST anomalies are present in the central-eastern tropical Pacific (Fig. 7d). Due to these negative SST anomalies in the equatorial CP, the reduction in the northern Hemisphere northeasterly trade winds retreated from the west to near and east of the dateline, and the atmospheric circulation remains a normal state in the WNP (Fig. 7d). Furthermore, the positive SST anomalies in the WNP almost returned into a normal state, which is not conducive to maintenance of the WNPC.

The composite analysis indicates that the WNPC peaks in the spring and can last into the following summer during the first year. WNPC is induced by SST warming over WNP and maintained by *in-situ* air-sea interactions. Equatorial central-eastern Pacific SST anomaly is also a key factor in causing and maintaining WNPC. The SST cooling in the equatorial CP could induce a lower tropospheric abnormal anticyclone in the northwest regions of these anomalous cold SSTs and weaken the northwest trade winds, which could reduce evaporation and latent heat flux, leading to SST warming in the WNP. Because the anomalous SST decays rapidly in the second year over these regions of the tropical Pacific, WNPC cannot persist and disappears in spring. In addition, due to the anomalous lower troposphere horizontal winds and 500 hPa vertical motion, the meridional signals in the second year are weak (Figs 6 and 7), and the abnormal signals in the tropics are limited to the tropics, which may have little impact on southern China.

4 Summary and discussion

To illustrate the different effects on precipitation over China between the first and second years of multiyear La Niña events, we investigated composited anomalous SST and atmospheric circulation based on observational and reanalyzed data. In this study, we noted that there is little difference in precipitation between the two consecutive winters during multiyear La Niña events (Figs 3a, b), due to little difference observed in the pattern of anomalous SST and 850 hPa wind (Figs 7a, b). However, for multiyear La Niña events, there are significantly different precipitation anomaly patterns over southern China between the first

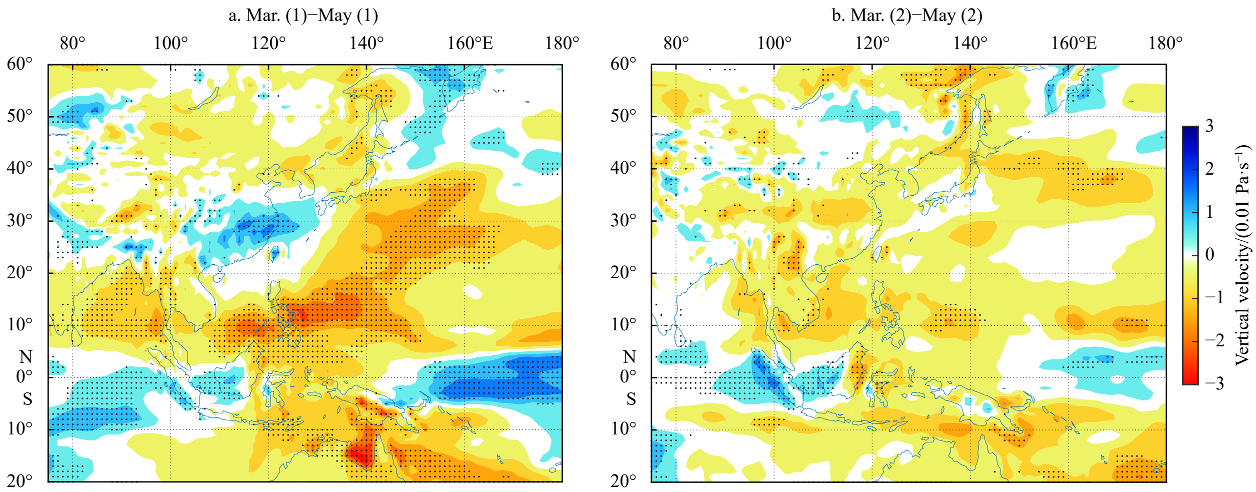

Fig. 6. Vertical velocity of air at 500 hPa; red regions are anomalous ascending motion and blue regions are anomalous descending motion. Dots indicate the areas where vertical velocity anomalies are statistically significant above a 90% confidence level.

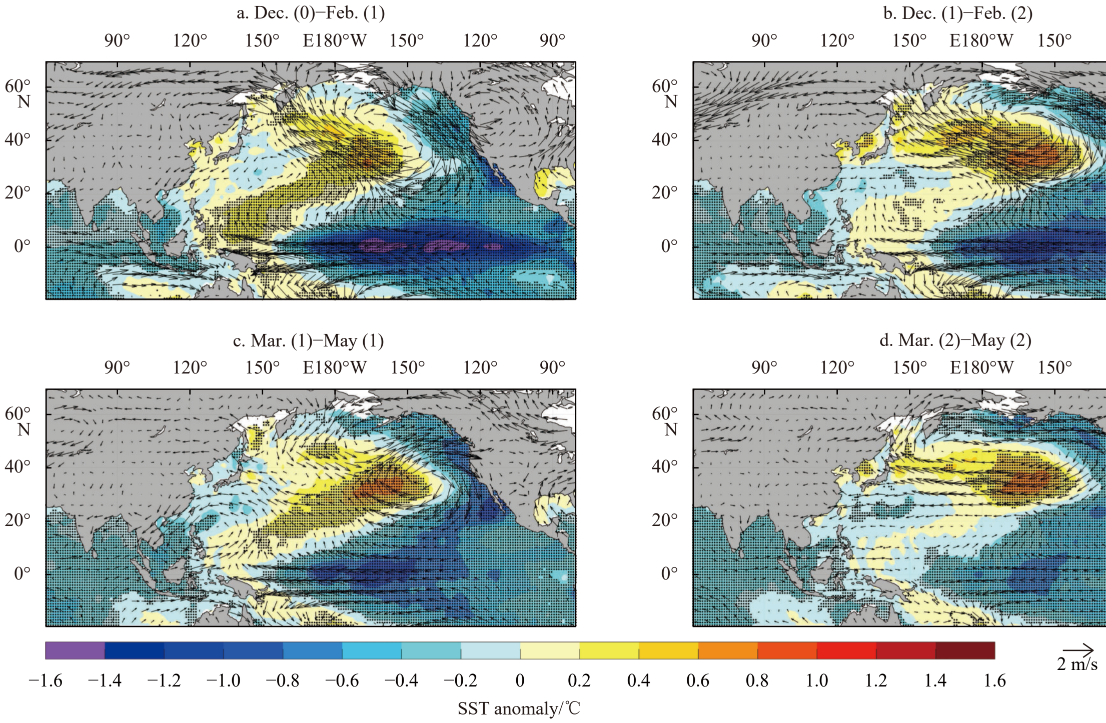

Fig. 7. Observed SST anomalies (shading, ℃) and wind at 850 hPa (vector, m/s) in the first and second winters (a and b) and spring (c and d) of composite multiyear La Niña events. Dots indicate the areas where SST anomalies are statistically significant above a 90% confidence level.

and second springs. Southern China tends to receive statistically below-normal precipitation in the first spring, but there is a tendency for above-normal precipitation in the second spring, which is different from a conventional La Niña event. Accompanied by the intensity of SST anomalies weakening from the first to the second year, the WNPC also weakens in the second spring. The weaker general circulation anomalies decay rapidly in the second spring, accompanied by weaker and quickly decaying SST anomalies in the tropical Pacific, especially WNP. This weaker and rapidly decaying atmospheric circulation anomaly in the WNP in the second spring cannot maintain northerly wind anomalies in southern China. This difference in lower-troposphere circulation could cause a precipitation deficit in the first spring and plentiful precipitation in the second. The difference in WNPC between the two springs may be due to different tropical Pacific SST anomalies. WNPC could be impacted by IO through Indo-Western Pacific Ocean capacitor (Xie et al., 2009, 2016) and interbasin coupled atmosphere-ocean interaction across the tropical IO and WNP (Wang et al., 2013, 2017) in decaying summer. And the different WNPC appears to have little to do with IO SST anomalies in spring, because the same pattern and amplitude of anomalous SSTs and horizontal winds are observed over the IO in these two consecutive springs (Figs 7c, d). To provide quantitative results, we defined the WNPC index as the spring (March-April-May) mean 850 hPa geopotential height averaged over the anomalous circulation center (13°–23°N, 115°–145°E). The correlation between spring precipitation and the WNPC index is high (r = 0.47, above the 99% confidence level) (Fig. 8b). Moreover, the correlation between precipitation and the Niño3.4 index is +0.34 at the 90% confidence level (Fig. 8c).

In addition, there is a large difference in anomalous spring precipitation between single-year La Niña events and the first year of multiyear La Niña events. There is widely occurring drought in the southern Qinling-Huaihe River basin during multiyear La Niña events (Fig. 3a). Whereas for the single-year La Niña, there is also below-normal precipitation in many areas. But the precipitation anomaly areas are scattered with below-normal precipitation in some regions of southern China and the Huanghe River-Huaihe River basin and above-normal precipitation in the middle and lower reaches of the Changjiang River (Fig. 8a). The corresponding general circulation is also different. In the spring of single-year La Niña events, the northeasterly wind anomalies generated by the WNPC are weak in southern China, and the center of the WNPC moves northeast to the Kuroshio extension area. These differences may be caused by the different SST evolution characteristics of La Niña. The difference in the above two types of La Niña events in spring indicates that the study of multiyear events is of great significance to improve the spring prediction.

According to this study, multiyear La Niña events tend to cause long-lasted droughts over southern China from the peak winter to the following spring. But the prolonged drought is not found in the second year. Such a prolonged drought causes great economic and social damage in the first year. The multiyear La Niña events maybe predictable 18 to 24 months in advance (DiNezio et al., 2017). Therefore, it is necessary to study the different climate impacts and mechanisms between two consecutive years to improve their predictability.

All multiyear La Niña events from 1901–2015 were analyzed in this study. Only 10 events have been identified over the past 115 years, which limits the understanding of their impacts on global climate. To further verify the mechanism that affects precipitation over southern China, a coupled model must be applied in future work.

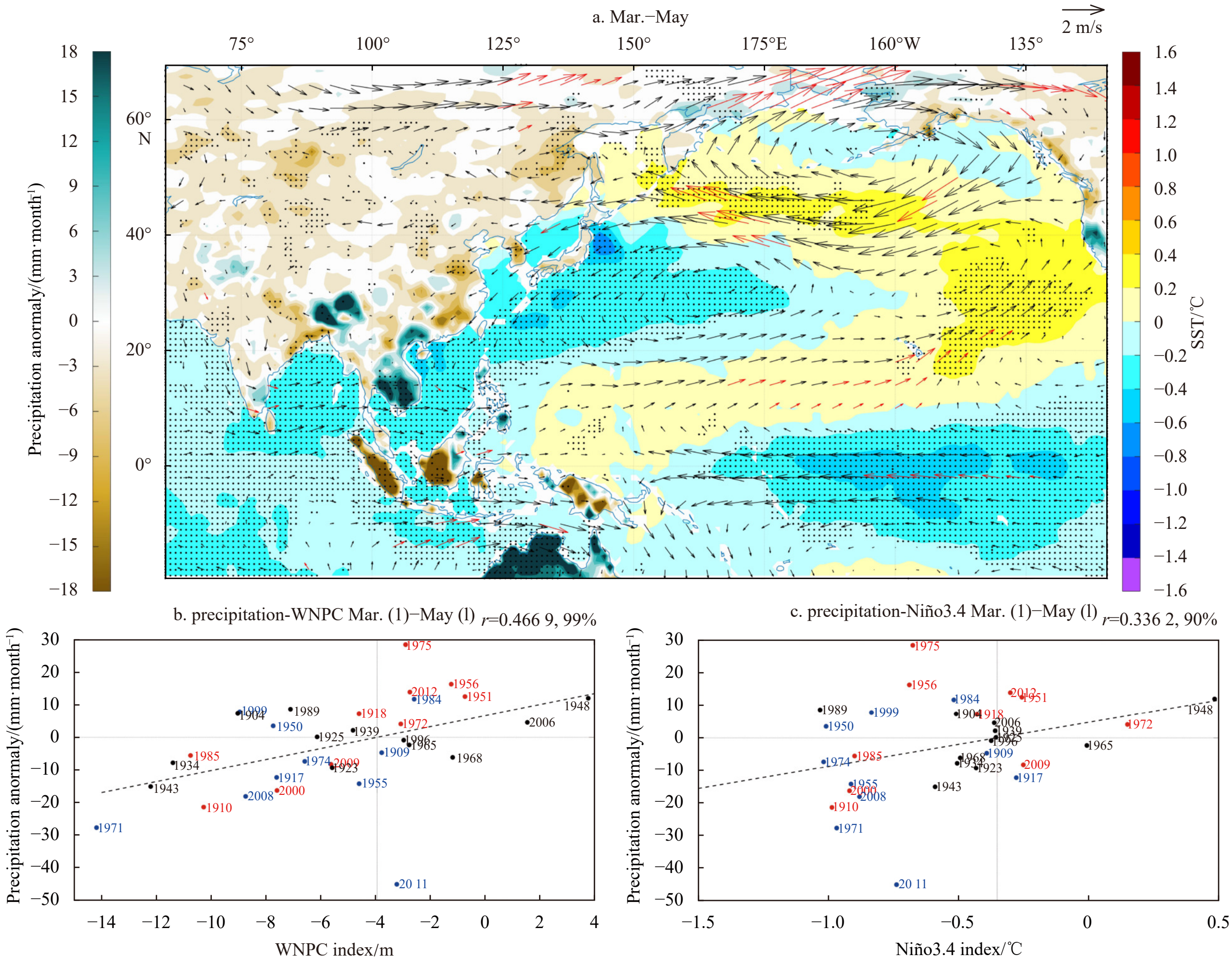

Fig. 8. Observed SST (shading in the ocean, ℃), precipitation (shading in the land, mm/month) and 850 hPa wind anomalies (vector, m/s) in spring during single-year La Niña (a), precipitation and WNPC index and their correlation for the first (blue dot) and second (red dot) spring of multiyear La Niña and single-year La Niña (black dot) (b), and precipitation and Niño3.4 index and their correlation (c). Red vectors and dots in a indicate the areas where 850 hPa wind anomalies and SST/precipitation anomalies are statistically significant above a 90% confidence level, respectively.

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