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Interdecadal Modulation of the Influence of La Niña Events on Mei-yu Rainfall over the Yangtze River Valley

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ABSTRACT

The aim of this study was to investigate changes in the relationship between mei-yu rainfall over East China and La Niña events in the late 1970s, a period concurrent with the Pacific climate shift, using mei-yu rainfall data and the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis. This relationship was modulated by the climate shift: Before the 1977/1978 climate shift and after the 1992/1993 climate shift, mei-yu rainfall levels were above normal in most La Niña years, whereas during the period 1979–1991, mei-yu rainfall was usually below normal levels in La Niña years.

Both composite analyses and results from an atmospheric general circulation model show remarkable detail in terms of La Niña's impacts on mei-yu rainfall in the late 1970s due to the change in the mean climatic state over the tropical Pacific. After the late 1970s, the tropical Pacific SSTs were warmer, and the mean state of low-level anticyclone circulation over the western North Pacific (WNP) weakened. Superimposed on La Niña–related cyclonic anomaly over the WNP, anticyclonic circulation weakened. Prior to the late 1970s, the mean state of low-level anticyclone circulation over the WNP was stronger and was less affected by La Niña–related anomalous cyclones. Anticyclone circulation may have brought moisture to the Yangtze River valley, leading to above-normal rainfall.

Key words: mei-yu, decadal modulation, La Niña

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1. Introduction

Mei-yu in June and July (Baiu in Japanese), generally begins in mid-June in the Yangtze River valley (YRV). The amount of rainfall during the mei-yu season determines the drought or flood conditions in the YRV. Previous studies have suggested that the mei-yu characteristics vary significantly both interannually and interdecadally (Chang et al., 2000a; Gong and Ho, 2002; Gu et al., 2009a).

The relationship between tropical Pacific sea-surface temperature (SST) and summer rainfall in China is complex, and it has been the subject of many studies over the past several decades (e.g., Chen et al., 2000; Huang et al., 2004; Chan and Zhou, 2005; Zhou and Chan, 2005; Lu et al., 2005, 2006; Li et al., 2006; Zhou et al., 2006; Wang et al., 2006; Zhou et al., 2007; Yuan et al., 2008a,b,c; Chen et al., 2009; Gu et al., 2009a, b; Lin et al., 2010; Zhou et al., 2010). Researchers have shown that the mei-yu rainfall anomaly

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is affected greatly by the SST anomaly (SSTA) in the eastern tropical Pacific (Huang and Wu, 1989; Shen and Lau, 1995; Chang et al., 2000a). Previous studies that focused on the impacts of El Niño on rainfall over China (Huang and Wu, 1989; Zhang et al., 1996, 1999; Chang et al., 2000a; Wang et al., 2000) found that mei-yu rainfall increases significantly in the summer after El Niño events. It has been shown that above-normal rainfall over the YRV is preceded by a warm equatorial East Pacific during the previous winter (Shen and Lau, 1995; Chang et al., 2000a). Wang et al. (2001) further suggested that the influence of ENSO on East Asian summer rainfall varies with the phase of an ENSO cycle. The weak western North Pacific (WNP) summer monsoon during the decay of an El Niño suppresses convection along 10°–20°N and enhances rainfall along the mei-yu/Baiu front. The notable regime shift of mei-yu rainfall in the 1970s was closely associated with the variation of the SST in the eastern tropical Pacific and tropical Indian Ocean (Gong and Ho, 2002).

Although the East Asian summer monsoon (EASM) was greatly affected by ENSO, the ENSO-related potential predictability of the EASM was lower in the 1980s than in the 1960s and 1970s (Wu and Hu, 2000). Results of recent studies have pointed to the frequency of El Niño and La Niña occurrences, showing decadal variability in the last century (Wang et al., 2009). Tanaka (1997) showed that the maximum negative correlation coefficient between the WNP monsoon and mei-yu/Baiu rainfall has been increasing since 1978. The correlation of summer rainfall over the YRV with previous winter's eastern tropical Pacific SST did not show noticeable change in the late 1970s (Chang et al., 2000a, b; Wu and Wang, 2002). Nevertheless, less attention has been paid to the variation of mei-yu rainfall when La Niña occurs. During the La Niña events in 1954 and 1996, the mei-yu rainfall levels in the Yangtze River region were as high as 3727 mm and 2943 mm, respectively. Notbaly, mei-yu rainfall levels increased during some La Niña events. Has the correlation of mei-yu rainfall with La Niña changed? The purpose of our study was to understand the impact of La Niña on mei-yu rainfall and its possible causes.

The paper is organized as follows. The data sets and methods are described in section 2. The relationship between La Niña and mei-yu is given in section 3. In section 4, differences of atmospheric circulations in La Niña events are compared. Results based on an atmospheric general circulation model (AGCM) were used to examine the main factors affecting the relationship between La Niña and mei-yu rainfall, which is discussed in section 5. Conclusions and discussion are given in section 6.

2. Data sets and methods

The annual mean mei-yu data from 1885 to 2005 was acquired from the National Climate Center of China Meteorology Administration (NCC CMA). This data included the precipitation, duration, and start and end dates of the mei-yu season. The data set was constructed by averaging the data at five stations, namely Shanghai (31.12°N, 121.26°E), Nanjing (32.03°N, 118.46°E), Wuhu (32.03°N, 118.46°E), Jiujiang (29.43°N, 115.59°E), and Wuhan (30.37°N, 114.20°E). The observation data sets used in this study included the monthly mean SST from the period 1870–2003 from the British Meteorological Office (HadISST1; horizontal resolution 1°×1°; Rayner et al., 2003). An upgraded version of the Hadley Centre's monthly historical mean sea-level pressure data set (HadSLP2; horizontal resolution 5°×5°) for the period 1850–2004 was used (Allan and Ansell, 2006). The geopotential height and wind fields at lower and middle levels (1000 hPa and 500 hPa; resolution 2.5°×2.5°) were adopted from NCEP/NCAR reanalysis (Kistler et al., 2001). Finally, the NINO3.4 index was defined by the area-averaged SST anomalies over 5°S–5°N and 170°–120°W.

The spectral AGCM used in this study was the atmospheric component of the Flexible Global Ocean-Atmosphere-Land System model (FGOALS), originally from the version of Simmonds (1985), which was developed at the Laboratory for Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG) of the Institute of Atmospheric Physics (IAP; Wu et al., 1996). This global spectral model of R42 (128×108 Gaussian grid points, equivalent resolution of 2.8125° longitude × 1.66° latitude) had nine sigma (σ) levels, with the top level at 17 hPa (R42L9). This model employs a unique dynamic core that removes a reference atmosphere to reduce systematic errors due to truncation and topography. The parameterization package includes the Slingo et al. (1996) scheme for radiation, the Slingo (1980, 1987) cloud diagnostic scheme, the Holtslag and Boville (1993) boundary layer scheme, and the moisture convective adjustment scheme of Manabe et al. (1965). A simplified version of the Simple Biosphere model (SIB) of Sellers et al. (1986) was used for land-surface processes (Xue et al., 1991). A semi-implicit scheme with a time step of 15 min was used. Further details of the model are available in Wu et al. (1996).

To study the influence of the climate mean state changes on the relationship between La Niña and mei-yu rainfall, four experiments were designed, each with a simulation time period of 7 years. In Experiments 1 and 3, the specified SST forcing was comprised of climatological monthly-mean SST data derived from the period 1950–1975 for the first 5 years of the simulation. In the year 6, SSTAs of −2°C and −1°C were superimposed on the NINO3.4 region, respectively. In Experiments 2 and 4, the climatological monthly mean SSTs from the period 1976–2003 were used as the specified forcing field for the first 5 years of the simulation. In the year 6, SSTAs of −2°C and −1°C were superimposed on the NINO3.4 region, respectively. Because this study focused on the impacts of La Niña on mei-yu rainfall in different climate mean states rather than the simulations of mei-yu rainfall on interannual variability, the derived differences between results in the year 7 and the average results from years 2–5 were taken as the response of the atmosphere to anomalous SST forcing. A similar simulation technique was used to analyze the impacts of the tropical Pacific–Indian Ocean temperature anomalies on Chinese and Indian climate (Yang et al., 2006).

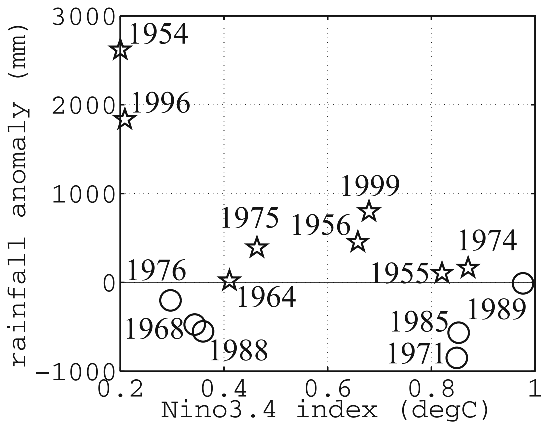

Fig. 1. The NINO3.4 index averaged over spring (MAM) and accompanying mei-yu rainfall anomalies in the same year when there was a La Niña phase in spring from 1954 to 2000. The circles and pentagons indicate the years when mei-yu rainfall was below and above normal levels, respectively. The NINO3.4 index was multiplied by −1.

3. Mei-yu variation in La Niña years

La Niña events between 1950 and 2000 were acquired from the NCC CMA (available at: http://ncc.cma.gov.cn/apn/history/class.htm). According to the NCC CMA, a La Niña event is defined by an SSTA in the NINO 1–4 regions persistently less than −0.4°C for 6 months. Compared with the La Niña events defined by NOAA or the Japan Meteorological Agency (JMA), the La Niña event in April–September 1978 was excluded by NCC CMA because of its short duration (<6 months). Notably, the La Niña episodes during the period 1950–2000 defined by NCC CMA were similar to those by defined by the NOAA and by JMA. According to Gong and Ho (2002), the anomalies of tropical eastern Pacific SSTs in spring are primarily responsible for the summer rainfall over the YRV. Therefore, we selected only the cases in which a La Niña condition was maintained from March to May (before the start of mei-yu), in order to study the relationship of La Niña events and the mei-yu rainfall variation in the same year. The analyzed La Niña years selected were the following: 1954, 1955, 1956, 1964, 1968, 1971, 1974, 1975, 1976, 1985, 1988, 1989, 1996, and 1999. Although the values of the NINO3.4 index averaged during spring in these years were negative, mei-yu rainfall anomalies were not deficient (Fig. 1). These La Niña cases can be categorized into two types. In the first type (8 years: 1954, 1955, 1956, 1964, 1974, 1975, 1996, and 1999), mei-yu rainfall remained above normal levels (type-1 La Niña). In the second type (6 years: 1968, 1971, 1976, 1985, 1988, and 1989), mei-yu rainfall was below normal levels (type-2 La Niña).

Figure 2 shows the composed SSTAs in the type-1 and type-2 La Niña years during the preceding DJF (Dec–Jan–Feb), MAM (Mar–Apr–May), and MJJ (May–Jun–Jul). Whether mei-yu rainfall anomalies were above-normal rainfall (type-1 La Niña) or below-normal rainfall (type-2 La Niña), negative SSTAs occurred in the eastern tropical Pacific in DJF and MAM prior to the respective mei-yu season. The summer monsoon rainfall anomaly over the YRV changed in the ENSO developing year and the following year for the period 1951–1980 (Huang and Wu, 1989). While investigating changes in the interannual relationship between ENSO and the summer rainfall over northern China and Japan in the late 1970s, Wu and Wang (2002) found that the effect of decaying phases of ENSO is more significant than that of developing phases. Figure 2 shows type-1 La Niña in the developing phase (Figs. 2a, c, and e), while type-2 La Niña is shown in the decaying phase (Figs. 2b, d and f). The relationship between La Niña and mei-yu rainfall seems to be associated with the La Niña phase. Because this issue is beyond the purpose of this study, it will be discussed in a future study.

In addition to the precipitation amount, mei-yu duration is another important parameter used to describe the mei-yu characteristics. Table 1 lists the duration of mei-yu in each La Niña year studied. The average duration of mei-yu in the period 1885–2005 was 21 days. Clearly, in type-1 La Niña the average duration of mei-yu of 30 days was longer than that in type-2 La Niña (19 days). However, the duration periods of mei-yu during type-2 La Niñas (1968, 1976, and 1989) were longer than the average duration during 1885–2005, and during type-1 La Niñas (1955, 1964, and

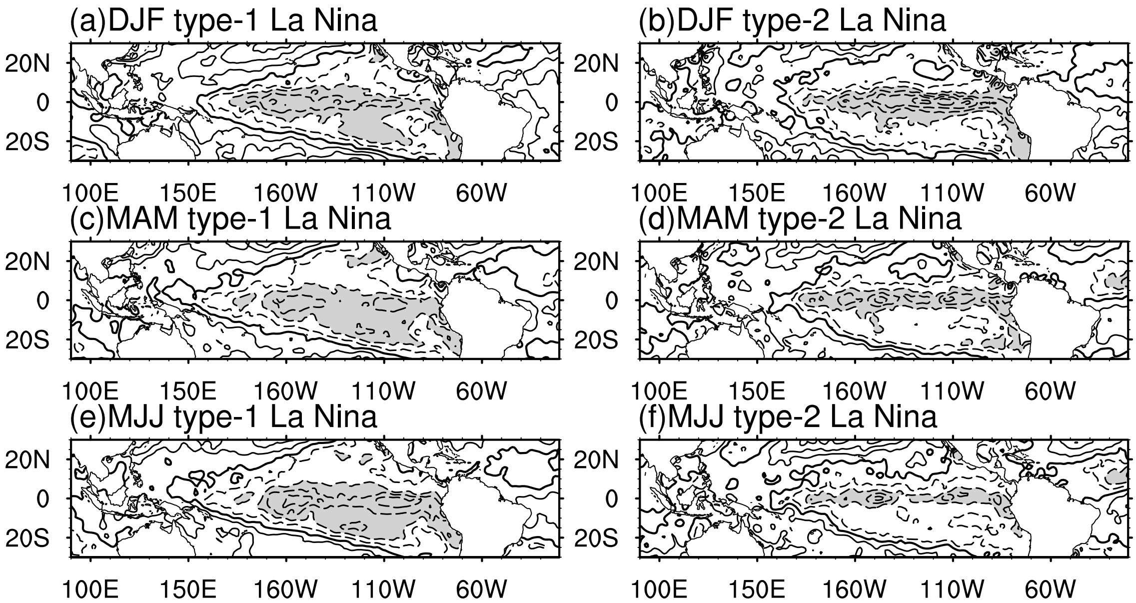

Fig. 2. Composite DJF (a, b), MAM (c, d) and MJJ (e, f) mean SST anomalies (contours) in (a, c, e) type-1 La Niña years and (b, d, f) type-2 La Niña years. Contour interval is 0.2°C. Shading indicates areas −0.2°C cooler than the norm.

1999) the duration periods of mei-yu were less than average. Particularly, although mei-yu persisted only 9 days in 1999, the rainfall anomaly was ∼800 mm, which was the third largest rainfall anomaly in type-1 La Niña overall. Therefore, type-1 and type-2 La Niña years classified in our study did not reflect the changes in the duration of mei-yu rainfall periods; rather they reflect the changes in rainfall intensity. In addition, Fig. 1 shows the relationship between the amplitude of the spring NINO3.4 index and mei-yu rainfall. The NINO3.4 index in type-1 La Niña years ranges from −0.1°C to −0.8°C. In type-2 La Niña years, the NINO3.4 index ranges from about −0.3°C to −1.0°C.

As has been well documented, the EASM exhibited the two major shifts around 1977/78 (Hu, 1997; Gong and Ho, 2002) and 1992/93 (Wu et al., 2010); both were significantly related to changes of the subtropical high over the WNP. In Fig. 1, the impacts of La Niña on mei-yu rainfall show similar climate shifts of the EASM. Before the first climate shift in 1977/1978, type-1 La Niña years were frequently observed, accounting for 2/3 of the total (six of the nine La Niña years). During the period 1979–1991, only three type-2 La Niña years (1985, 1988, and 1989) were found. After the second climate shift, around 1992–1993, type-1 La Niña (1996 and 1999) usually occurred. In the following section, the changing influences of La Niña on mei-yu rainfall in different climate regimes is discussed, and observation and model simulation results are presented.

Table 1. The mei-yu period in a La Niña year.

Type-1 La Niña		Type-2 La Niña	
Year	Duration (d)	Year	Duration (d)
1954	50	1968	26
1955	18	1971	6
1956	41	1976	25
1964	7	1985	15
1974	39	1988	13
1975	31	1989	30
1996	50		
1999	9		
Average	30	Average	19

4. Differences between circulations during type-1 La Niña and type-2 La Niña years

The correlation pattern of mei-yu rainfall and summer (June and July) sea level pressure (Fig. 3) shows that a significant, positive correlation center is located in the WNP. This is called an anomalous WNP anticyclone, and it conveys the effects of El Niño/La Niña to the East Asian climate (Wang and Zhang, 2002). Figure 4 shows the June–July mean 1000-hPa geopotential height and wind difference between the composite type-1 La Niña and type-2 La Niña years (type-1 La Niña years minus type-2 La Niña years). The differences shown in Fig. 4 indicate that the sea level pressure over the WNP in type-1 La Niña years was significantly higher than in type-2 La Niña years. An anticyclone center was located over the WNP and the region east of Taiwan. The stronger southerly winds

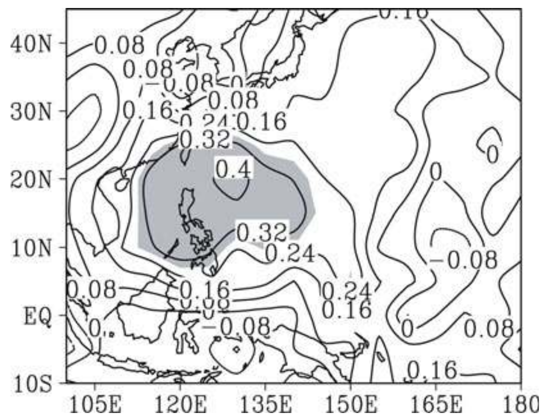

Fig. 3. Correlation of mei-yu rainfall and summer (June and July) sea level pressure during the period 1951–2000. Shading denotes a correlation significant at 95% confidence level.

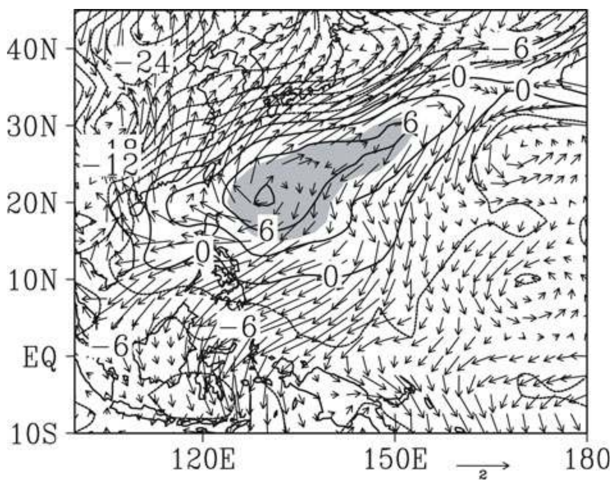

Fig. 4. The differences between type-1 La Niña years and type-2 La Niña years (type-1 La Niña minus type-2 La Niña) composite in June–July mean 1000-hPa wind (arrows) and geopotential height (contours). The type-1 La Niña years used for the composite include 1954, 1955, 1956, 1964, 1974, 1975, 1996, and 1999, and type-2 La Niña years include 1968, 1971, 1976, 1985, 1988, and 1989. The shaded areas indicate the region where the difference between type-1 La Niña and type-2 La Niña composite was statistically significant at 95% confidence level by *t*-test.

over the northern South China Sea and eastern China can bring more moisture to the YRV and thus increase the precipitation there. The mei-yu rainfall difference between the type-1 and type-2 La Niña years was 1239.12 mm (confidence level >99%).

The influence of La Niña on mei-yu rainfall changed around the 1977–1978 climate shift (Fig. 1). To uncover the different influences of La Niña on mei-

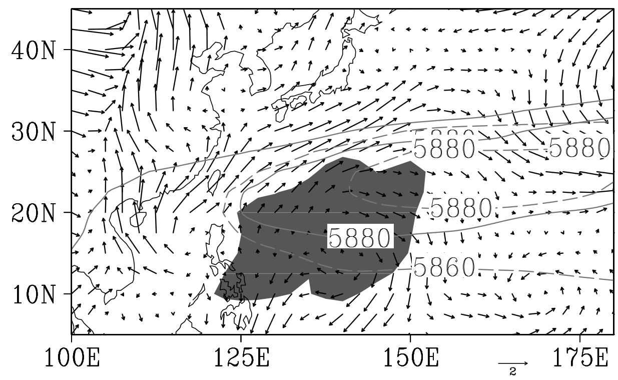

Fig. 5. Differences of June–July mean 1000-hPa wind (arrows) and sea level pressure (shadings) between the periods 1951–1975 and 1979–1991. Shading indicates regions where the differences in sea level pressure were positive. The dashed contour lines are the climatology of 5880 gpm and 5860 gpm during 1951–1975, and the solid contour lines are the climatology of 5880 gpm and 5860 gpm during 1979–1991.

yu rainfall before and after the climate shift, the June–July mean circulation in type-1 La Niña/type-2 La Niña was divided into two parts, one being the circulation anomalies, and the other, the mean circulation.

Figure 5 indicates that the differences of June–July mean 1000-hPa wind, sea level pressure, and western subtropical highs between the periods 1951–1975 and 1979–1991. After the 1977–1978 climate shift, the subtropical high enlarged and extended to the west (Gong and Ho, 2002). The climatological, June–July mean southerly wind over the eastern China was stronger in the period 1951–1975 than in 1979–1991. The climatological, June–July mean 1000-hPa wind difference between the two epochs demonstrates the anticyclone circulation over the WNP, indicating that the climatological sea level pressure over the WNP in the period 1951–1975 was higher than that in 1979–1991, a result consistent with that of Wu and Wang (2002). These large-scale atmospheric circulations resulted in more mei-yu rainfall during 1979–1991 than during 1951–1975; the difference was as much as 295 mm.

Wang et al. (2000) determined that the circulation that conveys the effects of El Niño (La Niña) to East Asia is the anomalous low-level anticyclone (cyclone) located over the WNP. However, the composite June–July mean 1000-hPa wind anomalies and geopotential height anomalies in type-1 La Niña years (Fig. 6a) differed from the results of Wang et al. (2000). In Fig. 6a, anticyclone anomalies, rather than cyclone anomalies, are found over the WNP. Also, the trough over East Asia is deeper, which leads to prevailing southerly anomalies, resulting in above-normal precipitation over east China and the YRV. The anomalous

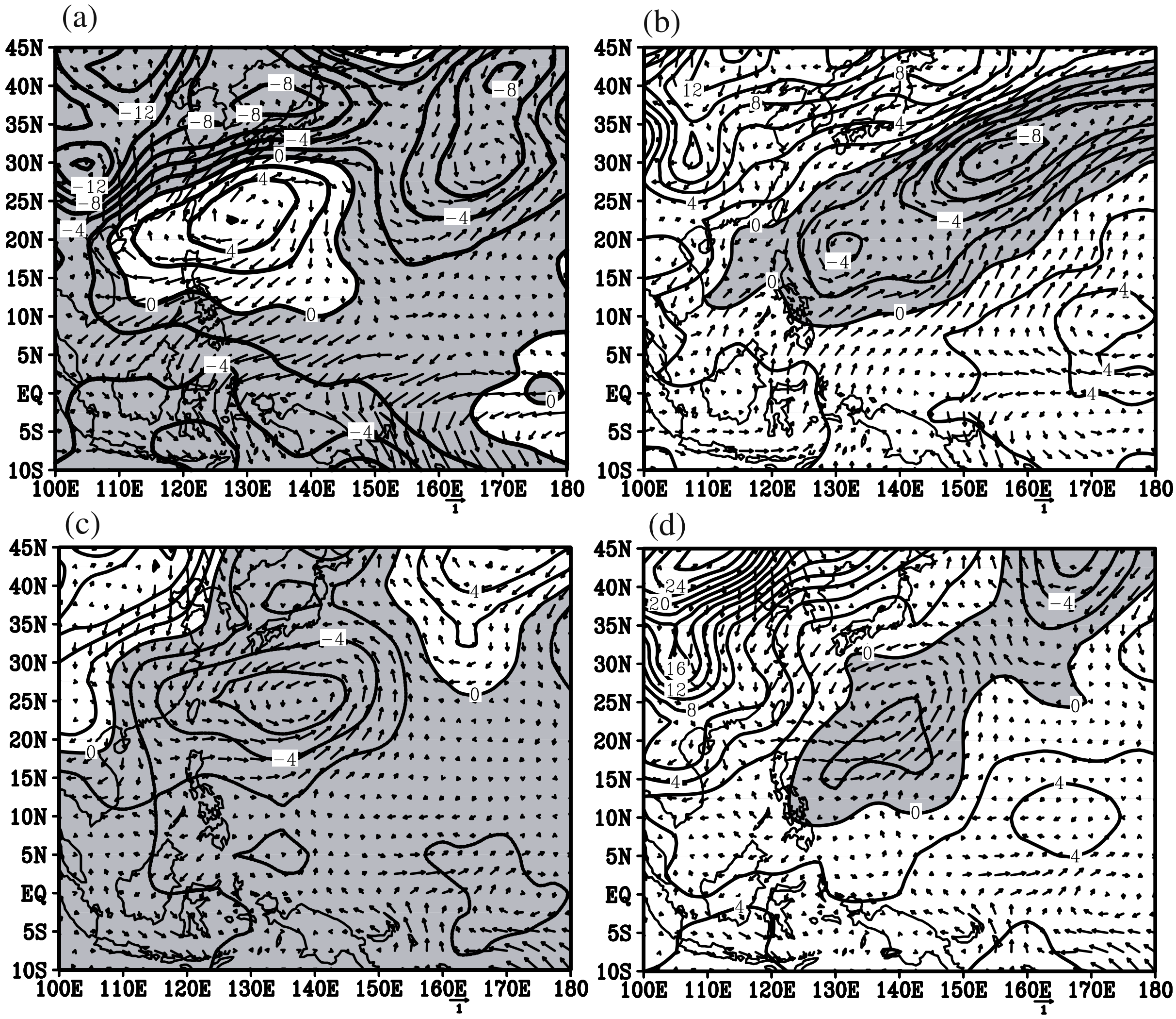

Fig. 6. Composite June–July mean 1000-hPa geopotential height anomalies (contours) and wind anomalies in type-1 La Niña years (a, c) and type-2 La Niña years (b, d). The anomalous fields in panels (a) and (b) were obtained by removing the climatological annual cycle in 1951–2000, and those in panels (c) and (d) were obtained by removing the climatological annual cycle in 1951–1975 and 1976–2000, respectively. Contour interval is 2 gpm. The negative values are shaded.

cyclone over the WNP related to La Niña was present in type-2 La Niña years (Fig. 6b), which is consistent with the results of Wang et al. (2000). Due to the reduced height of the trough over East Asia and the cyclone anomalies over the WNP, anomalous northerlies prevailed over eastern China, weakening the precipitation there. Considering the interdecadal variations of the climatological June–July sea level pressure over the WNP in the late 1970s (Fig. 5), the climate shift may explain the difference between type-1 La Niña and type-2 La Niña years over the WNP. In Figs. 6c and d, the annual cycles of 1951–1975 and of 1976–2000 were removed. In both type-1 La Niña and type-2 La Niña years, the trough over East Asia was dampened, and the anomalous cyclone was located over the WNP, which induced prevailing northerlies over East China and the YRV. Thus, the atmospheric anomalies induced by La Niña over the WNP are associated with the climate mean state, and the impacts of La Niña on mei-yu are closely related to the climate mean state. The mechanisms of how the WNP anomalous anticyclone or cyclone are established during warm or cold eastern tropical Pacific SSTAs are not discussed here.

5. Causes for different impacts of La Niña on mei-yu

Although the R42L9 model is rough, it still captured the main features of the spatial distribution and the temporal evolution of precipitation in the East

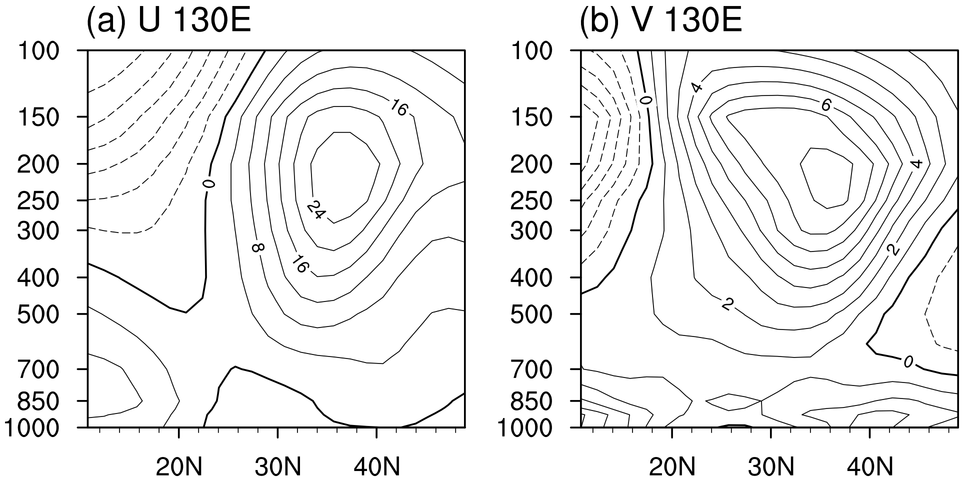

Fig. 7. Latitude–height cross section of June climatology (a) zonal wind (m s^{-1}) and (b) meridional wind (m s^{-1}) at 130°E. The climatological means are the averages of simulation results between the 2nd and 6th years.

Asian monsoon areas, and it simulated mei-yu-like summer rainfall to some extent (Wu et al., 2003b; Wang et al., 2004; Sampe and Xie, 2010). Zhuo et al. (2010) simulated 10-year mei-yu variations and found that the R42L9 model can reproduce the heavy precipitation centers over the Yangtze-Huai River Basin during mei-yu periods. However, the simulated mei-yu period was earlier and somewhat shorter than the observed mei-yu period, and the rainfall was underestimated. Before the model simulation, the simulation of a mei-yu front structure in terms of the latitude-height cross sections of zonal and meridional winds in June at 130°E was first compared with observation data (Ninomiya, 2000; Kitoh and Kusunoki, 2008). The simulated subtropical jet core of 24 m s^{-1} was located at 36°N, 200 hPa (Fig. 7a), which was less than that of the observation data (Kitoh and Kusunoki, 2008). Near the surface, a strong southerly wind component ($>$2 m s^{-1}) less than the observation data (Kitoh and Kusunoki, 2008) was found south of 20°N just to the south of the mei-yu rain band (Fig. 7b). Generally, a mei-yu front was simulated in this R42L9 resolution model to some extent.

Previous studies have identified a lead–lag relationship between the eastern tropical Pacific SSTA and the summer YRV rain anomalies (Shen and Lau, 1995; Chang et al., 2000; Yu et al., 2001; Gong and Ho, 2002). Yu et al. (2001) pointed out that the summer rainfall anomalies over the YRV are significantly related to the eastern tropical Pacific SSTA in previous period from November to March (Yu et al., 2001; Fig. 5). Gong and Ho (2002) found that the anomalies of tropical eastern Pacific SSTs in spring were primarily responsible for the summer rainfall over the YRV. Moreover, Fig. 2 shows the composed SSTA in the type-1 La Niña year and type-2 La Niña year during the prior DJF, MAM, and MJJ periods. The negative SSTA in the eastern tropical Pacific was strong during DJF and MAM (Figs. 2a–d). However, during MJJ, the clearly cooler SSTA in the eastern tropical Pacific occurred in type-1 La Niña years (Fig. 2e) but not in type-2 La Niña years (Fig. 2f). Considering the closer relationship between the eastern tropical Pacific SSTA and mei-yu rainfall suggested by previous studies and the eastern tropical Pacific SSTA pattern preceding mei-yu shown in Fig. 2, we thus superimposed the SST anomalies from November to the following April in model simulations.

The model simulations of mean state were checked. The mean state changes of simulated low-level wind vector between 1951–1975 and 1976–2000 (figure not shown) were similiar to observation results shown in Fig. 5. The simulation of water vapor flux rather than precipitation was given in this study because the moisture transportation supplied a background of precipitation, one of the most important physical processes in mei-yu rainfall simulation (Emori et al., 2001). Figures 8a and d show the June–July mean water vapor flux anomalies at 1000 hPa with −2°C and −1°C SSTAs superimposed (Experiments 1 and 3) on the monthly mean SST climatology for the period 1951–1975 over the NINO3.4 region. When the SSTA in the eastern tropical Pacific was cold (−2°C) and lasted for 6 months (from November to the following April), an anticyclone anomaly was located over the WNP, and the trough over East Asia deepened, causing prevailing southwesterly winds over southern China.

The southwesterly winds brought more moisture

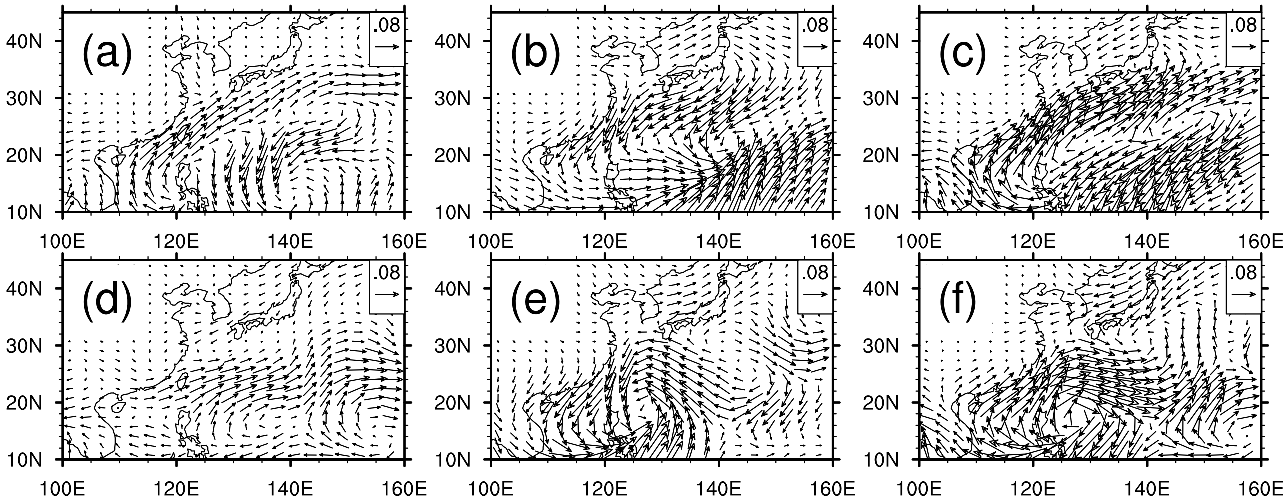

Fig. 8. 1000-hPa June–July water vapor flux (units: g m g^{-1} s^{-1}) anomalies in response to $-2°C$ SSTA (a, b) and $-1°C$ SSTA (d, e) forcing for the mean state in 1951–1975 (a, d) and 1976–2000 (b, e), respectively. (c) is the difference between (a) and (b) (a minus b), and (f) is the difference between (d) and (e) (d minus e). The water vapor flux is the multiplication of wind vector and specific humidity at 1000 hPa.

from the tropical ocean to East Asia, and the rainfall over the YRV thus increased (Fig. 8a). If the amplitude of La Niña was reduced to $-1°C$, although no significant anticyclone circulation anomalies were present over the WNP, the southwesterly prevailing winds over southeastern China still brought moisture to China. The rainfall over the YRV was inferred to be above normal in the 1951–1975 climatological monthly mean SST (Fig. 8d). Figures 8a and d indicates that even if an SSTA in the eastern tropical Pacific is in a cold phase (below mean SST) for the period 1951–1975, the prevailing southwesterly wind could bring sufficient moisture to southern China to cause mei-yu rainfall to increase. In contrast, the La Niña-related moisture transport anomalies over the WNP in June and July showed remarkable differences under mean SST for the period 1976–2000 (Figs. 8b and e). A cyclone circulation over the WNP can be seen in the 1000-hPa wind anomalies with $-2°C$ or $-1°C$ SSTAs superimposed over the NINO3.4 region. The anomalous northeasterly and northerly winds prevailed over southern China and middle-eastern China, which restricted moisture transportation from the tropical ocean to East Asia; thus the rainfall anomalies over the YRV were below normal (Figs. 8b and e). In addition, the La Niña-induced large-scale atmospheric circulation anomalies were different in the two mean SST states (Figs. 8c and f). Whether with $-2°C$ or $-1°C$ SST anomaly forcing, the anticyclone anomalies over the WNP less than the 1951–1975 mean SSTs were clearly stronger than those less than the 1976–2000 mean SSTs. Moreover, the water vapor flux anomalies induced by a $-1°C$ SSTA (Fig. 8d) were less than those by a $-2°C$ SSTA (Fig. 8a) over southern China. The water vapor flux anomalies over southern China with a $-2°C$ SSTA superimposed (Fig. 8b) were larger than those with a $-1°C$ SSTA (Fig. 8e). Therefore, the amplitude of the SSTA only influenced the amplitude of moisture transportation and the intensity of rainfall anomaly.

In summary, the model results showed that the changes in the relationship between La Niña and mei-yu rainfall are not correlated with the intensity of SSTA in the eastern tropical Pacific, but rather they depend on the mean state of tropical Pacific SSTs. Before 1976–1977, when the tropical Pacific mean SSTs were colder, the mei-yu rainfall was more associated with the ENSO cold phase; the mean tropical Pacific SSTs in the late 1970s were warmer than the period before 1976–1977, so the mei-yu rainfall was less.

6. Discussion and conclusions

Previous studies have shown the equatorial eastern Pacific SSTA to be positively correlated with mei-yu rainfall. In this study, the correlation between La Niña and mei-yu rainfall was investigated. When the eastern tropical Pacific SSTA in spring is in a cold phase, mei-yu rainfall is above normal in some La Niña years as well as in El Niño years. Being different from El Niño, mei-yu rainfall variations do not show a significant relationship with the phases of La Niña. We found that the impact of La Niña on mei-yu rainfall is modulated by the climate shift. The type-1 La Niña years (i.e., when rainfall was above normal) were frequently observed before the 1977/1978 climate shift and after 1992/1993 climate shift, whereas the type-2 La Niña years, i.e., when rainfall was below normal, usually occurred during 1979–1991.

By analyzing the changed relationship between ENSO and the YRV summer monsoon rainfall, Chang et al. (2000a, b) suggested that ENSO can impact intensity and westward extension of the western Pacific 500-hPa subtropical ridge, which results from the anomalous Hadley and Walker circulations and the atmospheric Rossby wave. The La Niña–related atmospheric circulations show that the low-level anticyclone over the WNP plays an important role in conveying the effects of La Niña to the mei-yu. Both composite analyses and AGCM results show that the remarkable change in the effects of La Niña on mei-yu rainfall in the late 1970s was due to the change in the climatic mean state over the tropical Pacific. The amplitudes of SSTA in the eastern tropical Pacific can affect only the intensity of rainfall anomaly.

The different impacts of La Niña on mei-yu can be explained as follows. Due to the warmer mean tropical Pacific SSTs in the period 1976–2000 than that of 1951–1975, the mean anticyclone circulations at low levels around the WNP were reduced. La Niña may have resulted in a cyclone anomaly over the WNP (Wang et al., 2000). The combined effects of the mean anticyclone circulation during the period 1976–2000 and the anomalous cyclone caused by La Niña around the WNP may have reduced the intensity of the anticyclonic circulation over the WNP. The weak southerly winds restrained the moisture supply from the ocean, leading to a decrease in mei-yu rainfall. However, before 1976/1977, because the stronger mean anticyclone circulation around the WNP was less affected by the anomalous cyclone caused by La Niña, the warm and wet air could reach the YRV, resulting in more mei-yu rainfall during La Niña events.

Notably, rainfall anomalies in 1954 and 1996 were much larger than those in 1955, 1956, 1964, 1974, 1975, and 1999. Likewise, 1971 had larger anomalies than did 1968, 1976, 1985, 1988, and 1989. These quantitative differences may be related to the collective impacts of La Niña and other climate systems. Admittedly, El Niño/La Niña is not the exclusive climate system influencing mei-yu rainfall. Many other factors can influence mei-yu rainfall as well as El Niño/La Niña (Wu et al., 2003a; Gao et al., 2011), such as the Indian Ocean (Watanabe and Jin, 2002; Wang and Zhang, 2002; Boo et al., 2004; Li et al., 2008; Yuan et al., 2008b), Pacific Decadal Oscillation (PDO; Wei and Song, 2005), North Atlantic SST (Gu et al., 2009a; Wang et al., 2010), the western Pacific warm pool (Nitta, 1987; Nitta and Hu, 1996) or NAO/AO (Gong et al., 2001; Li et al., 2005). As shown in Fig. 2, it seems that the North Atlantic SSTA or PDO may be related to mei-yu rainfall anomalies, which will be discussed in future studies. It is very difficult to identify the exact contributions of climate systems on mei-yu rainfall. For example, although rainfall anomalies in 1954 were much larger than those in the other type-1 La Niña years (1955, 1956, 1964, 1974, 1975, 1996, and 1999), and in 1971 there were larger anomalies than in other type-2 La Niña years (1968, 1976, 1985, 1988, and 1989), La Niña in 1954 was relatively weaker than in 1971 (Fig. 1), and the larger SST anomalies occurred in the North Atlantic and North Pacific in 1954 and 1971 (figure not shown), which may have influenced mei-yu rainfall more than La Niña. Although mei-yu rainfall anomalies are influenced by many climatic systems, according to superimposition of the different SST anomalies in the eastern tropical Pacific, our simulation results show that the amplitude of the eastern tropical Pacific SSTAs were related to the intensity of mei-yu rainfall anomalies.

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