The Dipole Mode of the Summer Rainfall over East China during 1958–2001

HAN Jinping*[1,2] (韩晋平) and ZHANG Renhe[1] (张人禾)

[1]*State Key Laboratory of Severe Weather (LaSW),*

Chinese Academy of Meteorological Sciences, Beijing 100081

[2]*Nansen-Zhu International Research Centre, Institute of Atmospheric Physics,*

Chinese Academy of Sciences, Beijing 100029

(Received 16 January 2009; revised 31 March 2009)

ABSTRACT

By examining the second leading mode (EOF2) of the summer rainfall in China during 1958–2001 and associated circulations, the authors found that this prominent mode was a dipole pattern with rainfall decreasing to the north of the Yangtze River and increasing to the south. This reverse relationship of the rainfalls to the north and to the south of the Yangtze River was related with the meridional circulations within East Asia and the neighboring region, excited by SST in the South China Sea-northwestern Pacific. When the SST was warmer, the geopotential heights at 500 hPa were positive in the low and high latitudes and negative in the middle latitudes. The anticyclone in the low latitudes favored the subtropical high over the northwestern Pacific (SHNP) shifting southwestward, leading to additional moisture transport over southern China. The anomalous atmospheric circulations along the East Asian coast tends to enhance upward movement over the region. Subsequently, rainfall in southern China is enhanced.

Key words: second leading mode, rainfall, dipole pattern, sea surface temperature

Citation: Han, J. P., and R. H. Zhang, 2009: The dipole mode of the summer rainfall over East China during 1958–2001. *Adv. Atmos. Sci.*, **26**(4), 727–735, doi: 10.1007/s00376-009-9014-6.

1. Introduction

Summer rainfall variability in China is a hot topic in climate research. The rainfall is closely related with the East Asian summer monsoon (EASM). Many studies have revealed that the EASM experienced a distinct weakening in the late 1970s (Wang, 2001), characterized by a pronounced increase of the rainfall in the mid-lower reaches of the Yangtze River basin and decrease in North China (Huang et al., 1999; Gong and Ho, 2002; Zhang et al., 2004; Wang and Zhou, 2005). It was proposed that SST, especially ENSO, strongly influences the rainfall variation (Zhang et al., 1996; Hu, 1997; Weng et al., 1999; Chang et al., 2000a,b; Wu and Wang, 2002; Yang et al., 2005). Some studies also found the linkage between the Antarctic Oscillation (AAO) and summer rainfall in China (Wang and Fan, 2005; Fan, 2006; Sun et al., 2008). Additionally, the snow cover (Chen and Wu, 2000; Liu and Yanai, 2002; Wu and Qian, 2003; Zhang et al., 2004; Liu et al., 2004; Zhao et al., 2007; Wu et al., 2009), atmospheric aerosols (Xu, 2001; Menon et al., 2002) and ozone depletion (Zhou and Zhang, 2005) have been revealed to contribute to the climate shift. These studies showed that the dominant mode of the rainfall is featured by an increase near the Yangtze River and decrease in both northern and southern China.

Recently, however, this meridional three-center pattern in rainfall anomalies has appeared to change to a dipole pattern after the late 1980s (Ding et al., 2008; Zhang et al., 2008). Ding et al. (2008) examined the 9-yr running mean of the summer rainfall in the period of 1951–2004. A regime transition of the meridional rainfall mode from "+ − +" pattern to a dipole pattern in 1992 was found. Since that time, the rainfall in South China has remarkably increased.

*Corresponding author: HAN Jinping, hanjp@cams.cma.gov.cn

However, this fact alone does not demonstrate whether this dipole pattern is truly a robust dominant mode of the rainfall. Although Zhang et al. (2008) mentioned that the dipole pattern might be related to the SST in the northwestern Pacific, it is unclear how the dipole mode is connected with the SST. These questions will be explored in the present study, which is outlined as follows. Section 2 describes the data used in the study. The summer rainfall related with the dipole mode is presented in section 3. Section 4 concerns the circulation anomalies associated with the dipole rainfall mode, and is followed by a possible explanation of the SST's influence on the atmospheric circulation in section 5. Section 6 gives the summary.

2. Data and methods

Monthly rainfall data at 534 observational stations in China during 1958–2001 was obtained from the China Meteorological Administration (CMA). The atmospheric circulation data used here has a resolution of 2.5° × 2.5° and are from the ERA-40 Reanalysis of the European Centre for Medium-Range Forecast (ECMWF) (Simmons and Gibson, 2000). The sea surface temperature data at a resolution of 2.0° × 2.0° is from NOAA extended reconstructured SST (Smith and Reynolds, 2003).

EOF analysis is applied to distinguish the dominant modes of the summer rainfall in China for 1958–2001. Correlation, regression, and composite analyses for 1958–2001 are calculated to reveal the related atmospheric circulations. Correlation coefficients exceeding 0.3 are above the 0.05 significance level.

3. The summer rainfall associated with the dipole mode

By using EOF analysis for the rainfall in China during 1958–2001, we find dominant modes of the rainfall variation. The first leading mode (accounting for 14.3% variance) shows a meridional tripole pattern over East China with positive values in the lower reaches of the Yangtze River and negative values in North and South China (figure not shown). The second mode of the rainfall is a dipole rainfall pattern over East China (accounting for 11.6% variance) (Fig. 1a). The variation accounted by the third mode is 7.9%, which is considerably less than the first two modes. Hence, the third mode will not be discussed here. The first three eigenvalues of the EOF are λ_1=71691760, λ_2=58052596.0, and λ_3=39693756.0, respectively. According to North et al. (1982), EOF1 cannot be distinguished from the sample error, whereas EOF2 is distinguishable. It is well known that EOF analysis is sensitive to the sample size of the series. Although EOF1 is not a distinguishable mode for the period of 1958–2001, the triple pattern of the rainfall anomalies is still a dominant spatial distribution in other periods and has been widely investigated (Huang et al., 1999; Zhou and Yu, 2005). This study will focus on the second leading mode, EOF2.

The spatial pattern of EOF2 (Fig. 1a) shows a dipole distribution with negative values to the north of the Yangtze River and positive values to the south. This out-of-phase relationship of the rainfall suggests that summer precipitation is decreasing in the region north of the Yangtze River and increasing to the south during 1958–2001. The dipole mode can also be found in the summer rainfall trend (Fig. 2). Figure 2 shows that the rainfall to the south of the Yangtze River has an increasing trend with a maximum rate of 7 mm yr^{-1} during 1958–2001. Additionally, the dipole rainfall pattern is also found at the decadal time scale (Ding et al., 2008). This suggests that the dipole mode of the rainfall might be a prominent pattern of variation during 1958–2001.

The EOF2 time series displays a large interannual variability with a distinct increasing trend, especially after the late 1980s (Fig. 1b). The years when the amplitude of time series is greater than 1.0 are defined as positive years and those less than −1.0 are negative years. These criteria indicate 7 years with positive phase of this mode (1969, 1993, 1994, 1995, 1996, 1998, and 1999) and 8 years with negative phase (1958, 1963, 1972, 1978, 1981, 1985, 1989, and 1990). It is obvious that after 1990, the frequency of negative years is much greater than positive years.

Figure 3a shows the composite difference of the summer rainfall (the positive years minus the negative years, based on the above criteria). This difference has a dipole pattern with positive values to the south of Yangtze River and negative values to the north. The reverse relationship of the rainfall in northern and southern China can also be found from the rainfall averaged over the regions to the north and south of the Yangtze River, respectively (Fig. 3b). The stations involved are shown in Fig. 1a, with solid dots indicating locations to the south of theYangtze River and empty circles for those to the north. The correlation coefficient is −0.40. When linear trends are removed, the correlation coefficient is −0.34. Both results exceed the 0.05 significance level.

4. Atmospheric circulation anomalies

The rainfall anomalies are a reflection of the variation of the summer monsoon circulations. In this section, the circulation anomalies associated with the

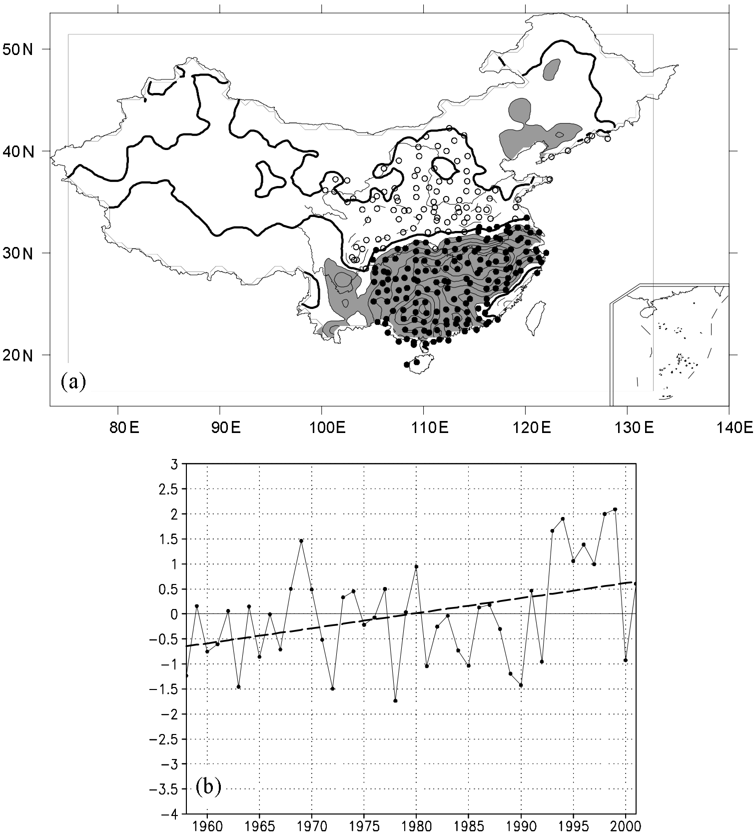

Fig. 1. The second leading mode of EOF analysis of the summer rainfall in China (EOF2) (1958–2001) (a) spatial distribution (the shaded areas are negative), and (b) corresponding time series (solid line with solid circles; the dashed line is the linear trend). The empty (solid) circles in (a) indicate the locations of stations representing regions to the north (south) of the Yangtze River.

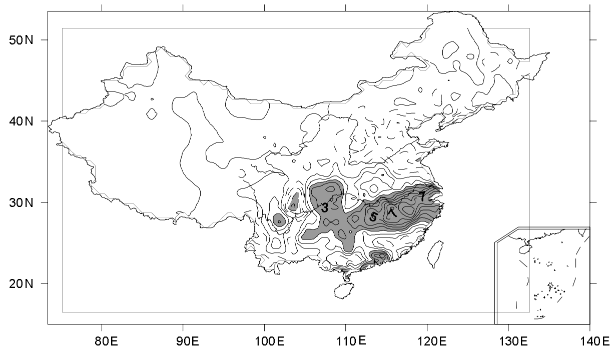

Fig. 2. Linear trend of the summer rainfall in China in 1958–2001 (units: mm yr^{-1}). The contour interval is 1 mm yr^{-1}. The shadings indicate values exceeding 2 mm yr^{-1}.

dipole rainfall pattern will be discussed to reveal the relationship between the atmospheric circulation anomalies and the rainfall pattern.

To investigate the circulations related to the dipole rainfall pattern, the composite 500-hPa geopotential heights and wind vectors at 850-hPa are calculated (Fig. 4a). Figure 4a shows a three-pole pattern along the East Asian coast, with negative values in the middle latitudes and positive values in both the high and low latitudes. The strengthened southwesterly winds turn to westerly flows at 30°N. This wind direction change is favorable for enhancement of vertical motion in southern China (Fig. 4b). Figure 4b shows the composite vertical velocity, indicating distinct upward movement in southern China. The strong upward movement is responsible for the positive rainfall anomalies in southern China. The meridional three-pole pattern is a typical anomalous circulation, known as the East Asian-Pacific (EAP) teleconnection pattern (Huang and Sun, 1992). There are positive geopotential height anomalies over the South China Sea and the western Pacific, and negative anomalies in the middle latitudes, which is favorable for the southward shifting of the strengthened subtropical high over the northwestern Pacific (SHNP).

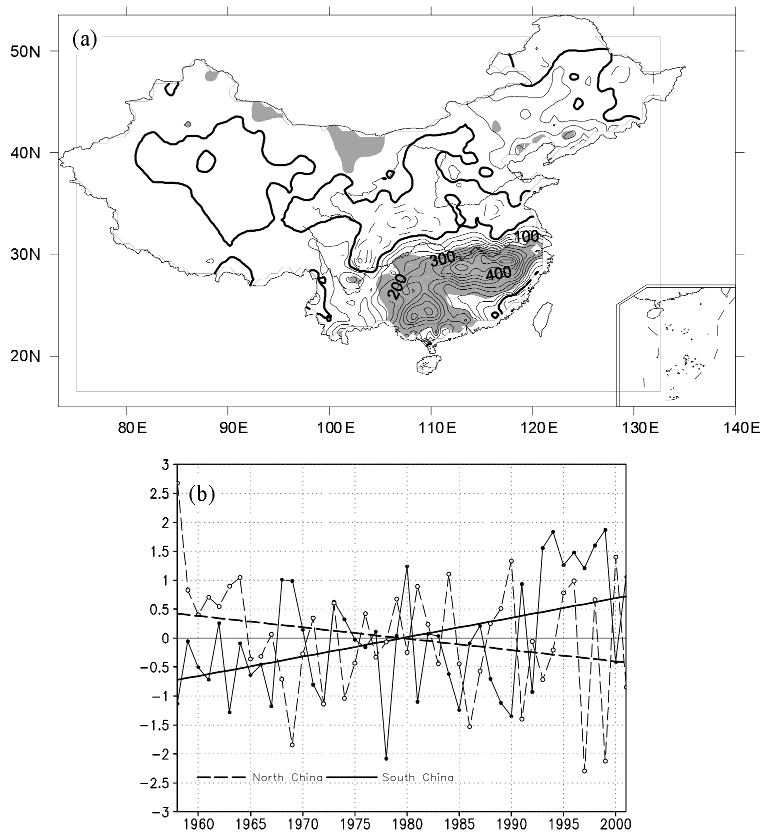

Fig. 3. (a) Composite difference of summer rainfall between positive and negative years (units: mm). Shaded areas indicate values above the 0.05 significance level. (b) The rainfall to the north (dashed line with open circles) and to the south (solid line with solid circles) of the Yangtze River. The dashed and solid lines are linear trends of the rainfall to the north and the south of the Yangtze River, respectively.

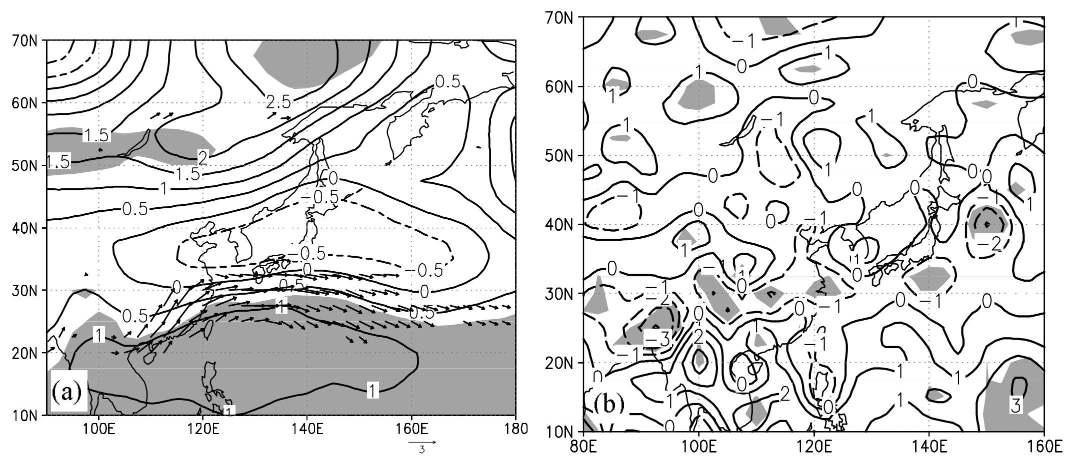

Fig. 4. Composite differences between the positive and negative years. (a) 500-hPa geopotential heights (contours) (units: gpm) and 850-hPa winds (vectors) (units: m s^{-1}). (b) The 500-hPa vertical velocities (units: Pa s^{-1}). Shading areas indicate values above the 0.05 significance level.

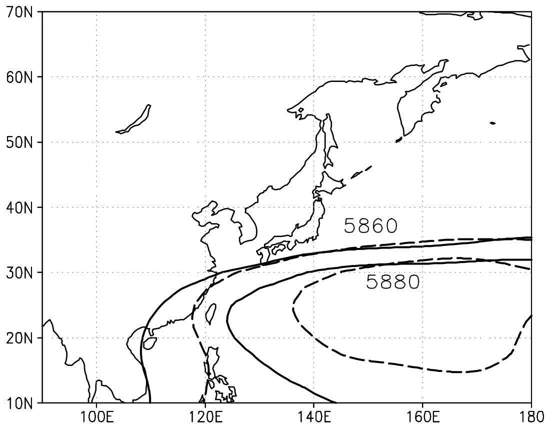

Fig. 5. Composite 500-hPa geopotential height for positive years (solid lines) and negative years (dashed lines) (units: gpm). The 5860 and 5880 contours represent the subtropical high over the northwestern Pacific.

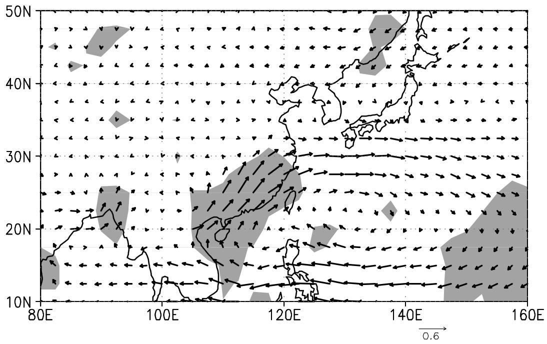

Fig. 6. Composite difference of 850-hPa moisture transport between positive and negative years (units: g m^{-1} s^{-1} Pa^{-1}). Shading areas indicate values above the 0.05 significance level.

The location of the SHNP, especially its western ridge, is typically considered a key factor influencing the summer rainfall belt in China. Figure 5 gives the composite SHNP in positive and negative years over East Asia. The position of the 5860- and 5880-gpm contours show that compared to the negative years, the SHNP moves more westward during the positive years (Fig. 5). The western shift of the SHNP tends to increase water vapor transport in southern China and decrease it to the north.

Water vapor transport is one of the key factors contributing to the rainfall anomalies. Figure 6 shows the difference of the moisture transport between positive and negative years. Compared with negative years, more moisture is transported to the south of the Yangtze River. The moisture transport is not significant to the north of the Yangtze River. This suggests that the moisture transport is closely related to the positive rainfall anomalies in the southern China.

5. A possible cause of the rainfall shift in the late 1980s

Studies on the East Asian summer monsoon by many investigators (Hu, 1997; Weng et al., 1999; Yang and Lau, 2004; Zhang et al., 2008) have suggested that warming in the northwestern Pacific and South China Sea is a key contributor to rainfall variation. This section is about to reveal the possible role of SST over the northwestern Pacific and South China Sea in relation to the dipole rainfall variation discussed above.

The correlation between the EOF2 time series and the global summer SST shows regions of significance in the northwestern Pacific, South China Sea, and the northern Indian Ocean, with the maximum correlation exceeding 0.5. This suggests the warming of SST in these regions is closely connected with the dipole mode of the rainfall variation (Fig. 7).

The averaged summer SST over the region north of 20°S with correlation coefficient greater than 0.3 (shaded area in Fig. 7) is defined as the WPSST index. Figure 8 shows that the WPSST index has an

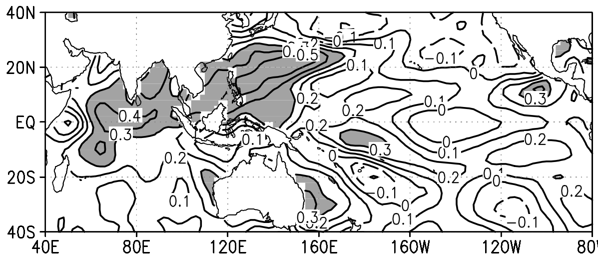

Fig. 7. The correlation between the EOF2 time series and the SST for the period of 1958–2001. Shading areas indicate values above the 0.05 significance level.

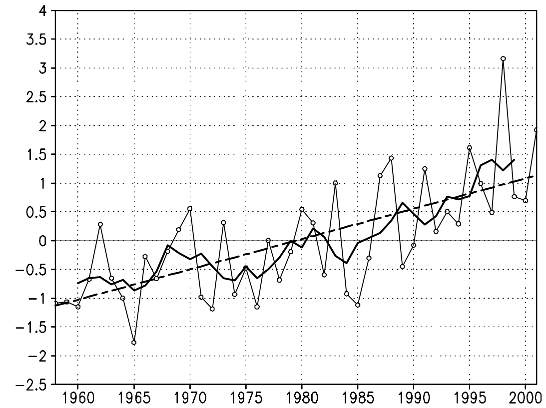

Fig. 8. WPSST index defined as averaged SST over the significant area (where correlation coefficients are greater than 0.3) in Fig. 7 (solid line with empty circles). The solid curve and dashed line are the 9-yr running mean and the linear trend, respectively.

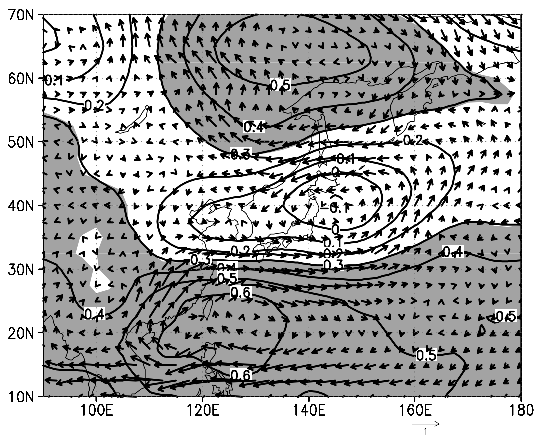

Fig. 9. Correlation of the 500-hPa geopotential heights (contours) and regressed 850-hPa wind vectors with the WPSST (vectors). Shading areas indicate values above the 0.05 significance level.

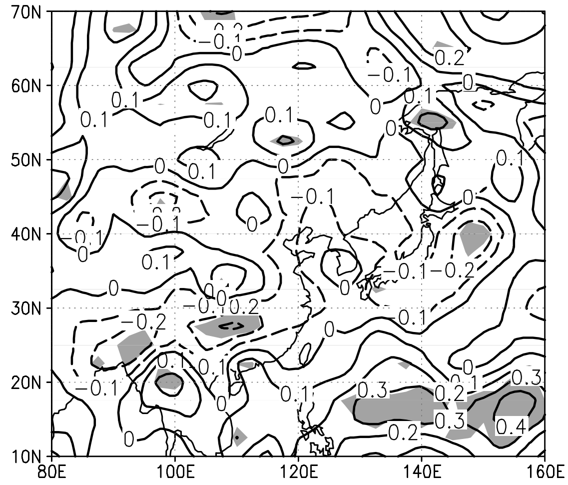

Fig. 10. Correlation of the 500-hPa vertical velocity with the WPSST. Shading areas indicate values exceeding the 0.05 significance level.

increasing trend with large interannual variability. It can be clearly seen that the WPSST sharply increases after the late 1980s. In other words, extensive warming in the South China Sea, the northwestern Pacific, and the northern Indian Ocean may play an important role in the rainfall changes, which occurred around the late 1980s.

Figure 9 shows the correlation of the 500-hPa geopotential heights and the regressed 850-hPa wind vectors with the WPSST index (linear trend removed). The correlated circulations along East Asia have a similar spatial pattern as Fig. 4a, containing the triple pattern of positive values in the low and high latitudes and negative values in the middle latitudes. The similarity of the circulations suggests that the WPSST is closely related with the circulation anomalies associated with the EOF2 mode of the rainfall. When the SST increases, the geopotential heights increase in the lower and high latitudes and decrease in the middle latitudes, which results in southwesterly onshore flows from the anticyclone in the South China Sea/northwestern Pacific, favoring more rainfall in South China. In fact, warming in the northwestern Pacific and South China Sea can excite the East Asian-Pacific (EAP) teleconnection pattern (Huang and Sun, 1992). An explanation is that the formation the circulation pattern shown in Figs. 4a and 9 is a response to the warming in the northwestern Pacific and South China Sea, which influences the East Asian summer monsoon.

The correlation of vertical velocity with the WPSST shows that, when the SST is warming, the excited EAP circulation favors a strengthening of upward motion in southern China (Fig. 10). The spatial distribution of correlations is similar to Fig. 4b. This suggests that warming of the SSTs has contributed to the circulations along the East Asian coast and to the increase of rainfall to the south of the Yangtze River.

The dipole rainfall mode, which has strengthened since the late 1980s, is connected with the EASM. Wu et al. (2008) examined the leading mode of the summer 850-hPa wind vectors, which is characterized by the western North Pacific-EASM pattern. This leading EASM mode has two interdecadal transitions in 1973 and 1989, respectively, and is closely related with the air-sea interaction in the South China Sea and the northwestern Pacific. Indeed, the SST in the northwestern Pacific increases after the late 1980s (Wu and Zhang, 2007). Therefore, the strengthened circulation excited by the warming of SSTs tends to enhance the rainfall to the south of the Yangtze River and suppress the rainfall to the north.

Previous studies suggested that the first leading mode (EOF1) of the rainfall in China during 1958–2001 also results in a meridional triple pattern. This does indicate that the locations of the SHNP and EAP teleconnection are strongly related with the anomalous rainfall pattern. There are, however, differences in circulation anomalies. The circulations connected with EOF1 and EOF2 are shown in Fig. 11. The 500-hPa geopotential heights have an EAP-like pattern along the East Asian coast in Figs. 11a and 11b. For EOF1, the geopotential heights in the middle and low latitudes are significant (Fig. 11a). For EOF2, the geopotential heights in the low and high latitudes are significant (Fig. 11b). The center in the middle latitudes is more westward in Fig. 11a than in Fig. 11b. Note that the geopotential heights in the middle

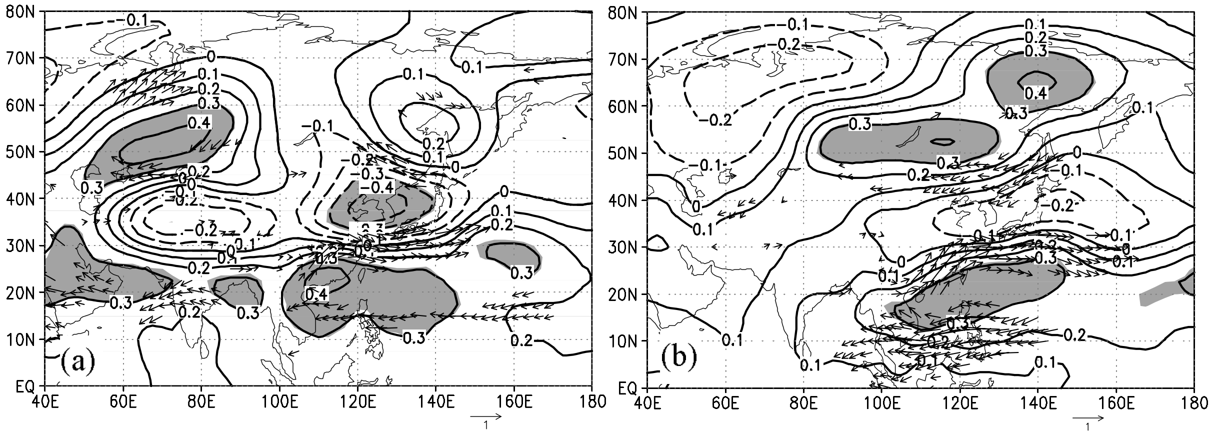

Fig. 11. Correlated 500-hPa geopotential heights and 850-hPa wind vectors with (a) EOF1 and (b) EOF2. Shading areas indicate values above the 0.05 significance level.

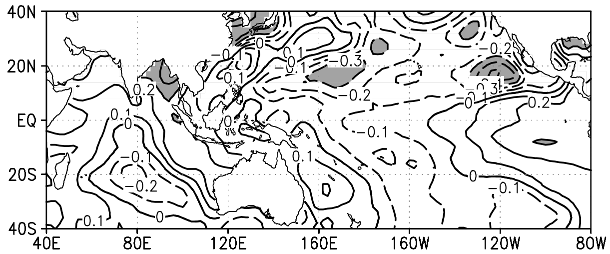

Fig. 12. The spatial distribution of the correlation between the EOF1 time series and the SST for the period of 1958–2001. Shading area indicates values above the 0.05 significance level.

and southern Asia are also key regions related with EOF1.

Additionally, the role of the global SST is much more complicated in connection with the EOF1 rainfall pattern. Figure 12 shows the correlation of global summer SST with EOF1. The Bay of Bengal is a significant region while the western Pacific and South China Sea are not. However, the latter is proposed to be the key area to excite the EAP pattern (Huang and Sun, 1992). Therefore, the circulations and contributors to rainfall variation associated with the EOF1 should be paid much greater effort in future investigation.

6. Summary

By examining the second mode of the summer rainfall in China during 1958–2001, we found that the rainfall shows a dipole spatial pattern with positive values to the north of the Yangtze River and negative values to the south. In recent decades, the rainfall has pronouncedly increased to the south and has remarkably decreased to the south. The correlation between these regions is −0.4 (−0.34 when linear trends are removed). This dipole rainfall mode is closely related with the circulation in East Asia and the neighboring regions. The correlation of 500-hPa geopotential heights and the regressed 850-hPa winds versus the EOF2 time series (linear trend removed) show a meridional three-pole distribution along the East Asian coast with the negative center in the middle latitudes and positive centers in the low and high latitudes, respectively. This pattern favors strengthening of the upward movements which contribute to heavier rainfall to the south of the Yangtze River.

The SSTs in the northwestern Pacific and South China Sea significantly influence the circulation anomalies. The correlation of the 500-hPa geopotential heights and regressed 850-hPa winds with the WPSST index have spatial patterns similar to the circulation change related to the EOF2. This suggests that a warming of the SSTs in these key regions can excite the East Asian-Pacific (EAP) teleconnection (Huang and Sun, 1992), leading to enhanced upward movement and resulting in heavy precipitation in southern China.

Acknowledgements. This study was jointly supported by the National Basic Research Program of China (Grant Nos. 2004CB418302 and 2009CB421404), and National Natural Science Foundation of China (Grant No. 40675058).

REFERENCES

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

Chang, C. P., Y. S. Zhang, and T. Li, 2000b: Interannual and interdecadal variations of the East Asian summer monsoon and tropical SSTs. Part II: Meridional structure of the monsoon. *J. Climate*, **13**, 4326–4340.

Chen, L. T., and R. G. Wu, 2000: Interannual and decadal variations of snow cover over Qinghai-Xizang Plateau and their relationships to summer monsoon rainfall in China. *Adv. Atmos. Sci.*, **17**, 18–30.

Ding, Y. H., Z. Y. Wang, and Y. Sun, 2008: Inter-decadal variation of the summer precipitation in East China and its association with decreasing Asian summer monsoon. Part I: Observed evidences. *International Journal of Climatology*, **28**, 1139–1161.

Fan, K., 2006: Atmospheric circulation in southern Hemisphere and summer rainfall over Yangtze River valley. *Chinese Journal of Geophysics*, **49**, 672–679. (in Chinese)

Gong, D. Y., and C. H. Ho, 2002: Shift in the summer rainfall over the Yangtze River valley in the late 1970s. *Geophys. Res. Lett.*, **29**, 1436, doi: 10.1029/2001GL14523.

Hu, Z. Z, 1997: Inter-decadal variability of summer climate over East Asia and its association with 500 hPa height and global sea surface temperature. *J. Geophys. Res.*, **102**, 19403–19412.

Huang, R. H., and F. Y. Sun, 1992: Impacts of the tropical western Pacific on the East Asian summer monsoon. *J. Meteor. Soc. Japan*, **70**, 243–256.

Huang, R. H., Y. H. Xu, and L. T. Zhou, 1999: Interdecadal variation and dry trend of summer precipitation in China. *Plateau Meteorology*, **18**, 465–476. (in Chinese)

Liu, H. Q., Z. B. Sun, J. Wang, and J. Z. Min, 2004: A modeling study of the effects of anomalous snow cover over the Tibetan Plateau upon the South Asian summer monsoon. *Adv. Atmos. Sci.*, **21**, 964–975.

Liu, X. D., and M. Yanai, 2002: Influence of Eurasian spring snow cover on Asian summer rainfall. *International Journal of Climatology*, **25**, 1075–1089.

Menon, S., J. Hansen, L. Nazarenko, and Y. F. Luo, 2002: Climate effects of black carbon aerosols in China and India. *Science*, **297**, 2250–2253.

North, G. R., T. L. Bell, R. F. Cahalan, and F. J. Moeng, 1982: Sampling errors in the estimation of EOFs. *Mon. Wea. Rev.*, **110**, 699–706.

Simmons, A. J., and J. K. Gibson, 2000: The ERA-40 Project Plan. ERA-40 Project Report Series 1, ECMWF, Reading, United Kingdom, 62pp.

Smith, T. M., and R. W. Reynolds, 2003: Extended reconstruction of global sea surface temperatures based on COADS data (1854–1997). *J. Climate*, **16**, 1495–1510.

Sun, J. Q., H. J. Wang, and W. Yuan, 2008: A possible mechanism for the co-variability of the boreal spring Antarctic Oscillation and the Yangtze River valley summer rainfall. *International Journal of Climatology*, doi: 10.1002/joc.1773. (in press)

Wang, H. J., 2001: The weakening of the Asian monsoon circulation after the end of 1970's. *Adv. Atmos. Sci.*, **18**, 376–386.

Wang, H. J., and K. Fan, 2005: Central-north China precipitation as reconstructed from the Qing Dynasty: Signal of the Antarctic atmospheric Oscillation. *Geophys. Res. Lett.*, **32**, L24705, doi: 10.1029/2005GL024562.

Wang, Y. Q., and L. Zhou, 2005: Observed trends in extreme precipitation events in China during 1961-2001 and the associated changes in large-scale circulation. *Geophys. Res. Lett.*, **32**, L09707, doi: 10.1029/2005GL022574.

Weng, H. Y., K. M. Lau, and Y. K. Xue, 1999: Multi-scale summer rainfall variability over China and its long-term link to global sea surface temperature variability. *J. Meteor. Soc. Japan*, **77**, 845–857.

Wu, B. Y., and R. H. Zhang, 2007: Interdecadal shift in the western North Pacific summer SST anomaly in the late 1980s. *Chinese Science Bulletin*, **52**, 2559–2564.

Wu, B. Y., R. H. Zhang, Y. H. Ding, and R. D Arrigo, 2008: Distinct modes of the East Asian summer monsoon. *J. Climate*, **21**, 1122–1138.

Wu, B. Y., K. Yang, and R. H. Zhang, 2009: Eurasian snow cover variability and its association with summer rainfall in China. *Adv. Atmos. Sci.*, **26**(1), 31–44, doi: 10.1007/s00376-009-0031-2.

Wu, T. W., and Z. A. Qian, 2003: The relation between the Tibetan winter snow and the Asian summer monsoon and rainfall: An observational investigation. *J. Climate*, **16**, 2038–2051.

Wu, R. G., and B. Wang, 2002: A contrast of the East Asian summer monsoon-ENSO relationship between 1962–77 and 1978–93. *J. Climate*, **15**, 3266–3279.

Xu, Q., 2001: Abrupt change of the mid-summer climate in central east China by the influence of atmospheric pollution. *Atmos. Environ.*, **35**, 5029–5040.

Yang, F. L., and K. M. Lau, 2004: Trend and variability of China precipitation in spring and summer: Linkage to sea-surface temperature. *International Journal of Climatology*, **24**, 1625–1644.

Yang, X. Q., Q. Xie, Y. M. Zhu, X. G. Sun, and Y. N. Guo, 2005: Decadal-to-interdecadal variability of precipitation in North China and associated atmospheric and oceanic anomaly patterns. *Chinese Journal of Geophysics*, **48**, 789–797. (in Chinese)

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

Zhang, R. H., B. Y. Wu, P. Zhao, and J. P. Han, 2008: The decadal shift of the summer climate in the Late 1980s over eastern China and its possible causes. *Acta Meteorologica Sinica*, **22**, 435–445.

Zhang, Y. S., T. Li, and B. Wang, 2004: Decadal change of the spring snow depth over the Tibetan Plateau: The associated circulation and its relationship to the East Asian summer monsoon rainfall. *J. Climate*, **17**, 2780–2793.

Zhao, P., Z. J. Zhou, and J. P. Liu, 2007: Variability of Tibetan spring snow and its associations with the hemispheric extratropical circulation and East Asian summer monsoon rainfall: An observational investigation. *J. Climate*, **20**, 3942–3955.

Zhou, S. W., and R. H. Zhang, 2005: Decadal variations of temperature and geopotential height over the Tibetan Plateau and their relations with Tibet ozone depletion. *Geophys. Res. Lett.*, **32**, L18705, doi: 10.1029/2005GL023496.

Zhou, T. J., and R. C. Yu, 2005: Atmospheric water vapor transport associated with typical anomalous summer rainfall patterns in China. *J. Geophys. Res.*, **110**, D08104, doi: 10.1029/2004JD005413.