Changed Relationships Between the East Asian Summer Monsoon Circulations and the Summer Rainfall in Eastern China

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ABSTRACT

In previous statistical forecast models, prediction of summer precipitation along the Yangtze River valley and in North China relies heavily on its close relationships with the western Pacific subtropical high (WPSH), the blocking high in higher latitudes, and the East Asian summer monsoon (EASM). These relationships were stable before the 1990s but have changed remarkably in the recent two decades. Before the 1990s, precipitation along the Yangtze River had a significant positive correlation with the intensity of the WPSH, but the correlation weakened rapidly after 1990, and the correlation between summer rainfall in North China and the WPSH also changed from weak negative to significantly positive. The changed relationships present a big challenge to the application of traditional statistical seasonal prediction models. Our study indicates that the change could be attributed to expansion of the WPSH after around 1990. Owing to global warming, increased sea surface temperatures in the western Pacific rendered the WPSH stronger and further westward. Under this condition, more moisture was transported from southern to northern China, leading to divergence and reduced (increased) rainfall over the Yangtze River (North China). On the other hand, when the WPSH was weaker, it stayed close to its climatological position (rather than more eastward), and the circulations showed an asymmetrical feature between the stronger and weaker WPSH cases owing to the decadal enhancement of the WPSH. Composite analysis reveals that the maximum difference in the moisture transport before and after 1990 appeared over the western Pacific. This asymmetric influence is possibly the reason why the previous relationships between monsoon circulations and summer rainfall have now changed.

Key words: western Pacific subtropical high, blocking high, East Asian summer monsoon, precipitation

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1. Introduction

China is located in the Asian-Australian monsoon region. Its weather and climate are greatly affected by monsoon systems, especially during boreal summer (June, July, and August). In this season, both the precipitation amount and the main rainfall belt are controlled by the summer monsoon systems. Among the monsoon circulations, the western Pacific subtropical high (WPSH), the East Asian summer monsoon (EASM), and the blocking high in higher latitudes are thought to be the key influencing factors.

Early in the 1950s, Chinese meteorologists began to explore the relationship between weather in China and the EASM systems (Huang, 1955; Chen, 1957; Tao and Chen, 1957; Ye and Zhu, 1958; Ye et al., 1959; Huang and Yu, 1961; Tao and Xu, 1962; Tao et al., 1962; Wang, 1962). Their results have been widely applied and referenced in both operational forecasting and scientific research. Since then, increasing attention has been paid to the EASM structure, its multi-timescale variations, its influencing elements, and its contribution to weather and climate of China, East Asia, and even the world (Chen et al., 1991; Zhao, 1999; Wu et al., 2002).

Zhou et al. (1964) analyzed the relationship be-

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tween the WPSH and the beginning/ending dates of Meiyu along the Yangtze River valley. Based on the 5880-gpm contour at 500 hPa, Zhao (1999) defined five WPSH indices for objective analysis of the WPSH. i.e., the area index, the intensity index, the ridge index, the northern boundary index, and the western boundary index. Based on these indices, it is revealed that both the position and intensity of the WPSH bear a significant relation to the Europe-Asia circulation pattern (Zhao, 1999). A more southward WPSH always corresponds to a positive-negative-positive pattern of the 500-hPa geopotential height anomaly from lower to higher latitudes in East Asia (Huang, 1992; Huang and Yan, 1999). Under this pattern, more summer precipitation will occur along the Yangtze River. On the contrary, if the WPSH is located further northward, drought will appear along the Yangtze River valley while floods occur in northern and southern China (Zhang, 1999; Zhao, 1999; Chen and Zhao, 2000; He et al., 2001; Wu et al., 2002; Zhang et al., 2003b). A recent study found that the WPSH has a close relationship with summer rainfall in Japan as well (Nagio and Takahashi, 2012).

Research on the EASM and its impacts on summer rainfall has a long history in China. Zhu (1934) innovatively analyzed the southeasterly monsoon and its influence on rainfall. Similar studies can be found in Tu and Huang (1944), Tao and Chen (1957), and Ye and Zhu (1958). Among all the circulation systems influencing heavy rainfall in Huaihe River and its south, the monsoon surge plays the most important role (Tao and Wei, 2007). The beginning dates of the rainy season in East Asian subtropical monsoon regions (China and Japan) are earlier than the dates in East Asian tropical monsoon regions (South China Sea and western Pacific) (Zhu et al., 1986; He et al., 2008). The interaction between the two monsoon systems causes the flood or drought in different areas (He et al., 2008). To better understand the interannual variation of EASM and its correspondence to summer precipitation, many EASM indices have been defined with focuses on different circulation systems (Guo, 1983; Shi et al., 1996; Zhao and Zhang, 1996; Sun et al., 2002; Zhang et al., 2003a). The results indicate that the summer rainfall from South to North China is most directly influenced by the EASM. A stronger EASM will result in more rainfall in southern and northern China, while a weaker monsoon will bring more rainfall along the Yangtze and Huaihe River valleys.

Besides the tropical and subtropical circulation systems, the blocking in higher latitudes also plays an important role in occurrences of drought and flood in China (Zhao, 1999; Chen and Zhao, 2000), as both its frequency and intensity directly affect the strength and location of cold air intrusion. Persistent blocking situations cause decreased rainfall in North China and more rainfall along the Yangtze River (Zhao, 1999; Chen and Zhao, 2000).

In summary, the EASM circulations largely influence the summer rainfall in China. Their close relationships have been widely applied in operational prediction of short-term climate in China (Zhao, 1999; Chen and Zhao, 2000). In traditional statistical forecast models, a La Niña event (i.e., lower SSTs in the equatorial eastern Pacific) is assumed to cause a weakened and more northward WPSH and a stronger summer monsoon, and finally brings floods to northern China and drought along the Yangtze River; on the other hand, a stronger and more southward WPSH, weaker monsoon systems, and more active blocking highs will together induce floods along the Yangtze River.

The results above have been used in climate prediction in China for many years. For example, based on the relations among the WPSH, the EASM, and the blocking activities, the extreme flood event along the Yangtze River in 1998 was successfully forecasted (National Climate Center, 1998). Nonetheless, the relationships among these systems have also been found unstable and nonlinear. In 1999, the WPSH was weaker than normal, but flood events also occurred along the Yangtze River, which is not consistent with the scenario mentioned above. Detailed examination of the cases in the past two decades indicates that the inconsistency appeared not only in 1999.

It is well known that interdecadal changes occurred in both the ocean and the atmosphere in the 1970s. Afterwards, the EASM weakened while the

WPSH strengthened (Han and Wang, 2007). Under this background, both the relationship between El Niño–Southern Oscillation (ENSO) and EASM, and the relationship between ENSO and summer rainfall in China, weakened (Wang, 2001; Gao et al., 2006; Wang and He, 2012). Have the relationships between the EASM/WPSH/blocking and summer rainfall also changed? If the changes have indeed occurred, what are their implications for the traditional statistical climate prediction? In the following sections, these questions will be addressed.

2. Data

The observed monthly rainfall amounts at 743 Chinese stations are provided by the China Meteorological Administration. For data quality, only the stations for which the data are complete during 1961–2010 are selected for further study. In this paper, the representative stations for North China and the Yangtze River valley are the same as those in Chen and Zhao (2000). The atmospheric variables are obtained from the NCEP/NCAR reanalysis (Kalnay et al., 1996) and include 500-hPa geopotential height and 850-hPa horizontal wind on a 2.5° × 2.5° latitude-longitude resolution (http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html). According to the standard of World Meteorological Organization (WMO), the climate normals are the latest three-decade averages of climatological variables, i.e., 1981–2010. Thus, in this paper, all the anomalies are derived based on the climate normal of 1981–2010.

Monthly WPSH indices are provided by the National Climate Center of China. The EASM index is defined as the difference of the area-averaged 850-hPa zonal wind speed between the regions 10°–20°N, 100°–150°E and 25°–35°N, 100°–150°E (Zhang et al., 2003a). Following the definition of Zhao (1999), the 500-hPa geopotential height values averaged over 50°–60°N, 120°–150°E; 50°–60°N, 80°–110°E; and 40°–50°N, 40°–70°E are used as the Okhotsk blocking high intensity (OBHI), the Baikal blocking high intensity (BBHI), and the Ural blocking high intensity (UBHI), respectively.

3. Decadal changes of the relationships between EASM circulations and summer rainfall

Since the 1980s, a number of studies have reported that the leading mode of summer precipitation variability in China is an anti-phase interannual variation in the middle to lower reaches of the Yangtze River against that in South/North China. Compared with other regions, precipitation in South China is more vulnerable to both tropical cyclones and convection. Therefore, in this paper, only the precipitation along the Yangtze River and the precipitation in North China are analyzed so as to explore the decadal changes of the relationships between monsoon circulations and rainfall.

The EASM circulations have remarkable interannual and interdecadal variations (Miao and Lau, 1990; Qian, 2005; Ding et al., 2013). Figure 1a shows the time-longitude cross-section of the 500-hPa geopotential height anomaly along 20°–30°N, i.e., along the WPSH center. Distinct differences between certain time periods are revealed. During most summers before the 1980s, the anomalies were negative, while they became positive after 1980. Similar decadal changes are also found in the blocking highs (figures omitted). The changes may be attributed partly to the increase of sea surface temperature (SST) in the tropical regions. As shown in Fig. 1b, the SSTs in the western Pacific show a remarkable warming trend since 1990. The raised SSTs lead directly to the expansion of the atmospheric column and the increase of geopotential height. The correlation coefficient between the SST in the western Pacific warm pool area and the averaged 500-hPa geopotential height over 20°–30°N, 120°–150°E in JJA is over 0.4, exceeding the 95% confidence level. Thus, the WPSH also displays an enhancing and expanding trend. Influences of ENSO events on the WPSH can also be deduced from Figs. 1a and 1b. For example, during strong El Niño phases such as in 1983 and 1998, the WPSH is much stronger than normal.

In boreal summer, the climatological center of WPSH lies within 20°–30°N (figure omitted). Figure 2 shows the 21-yr running correlation coefficients

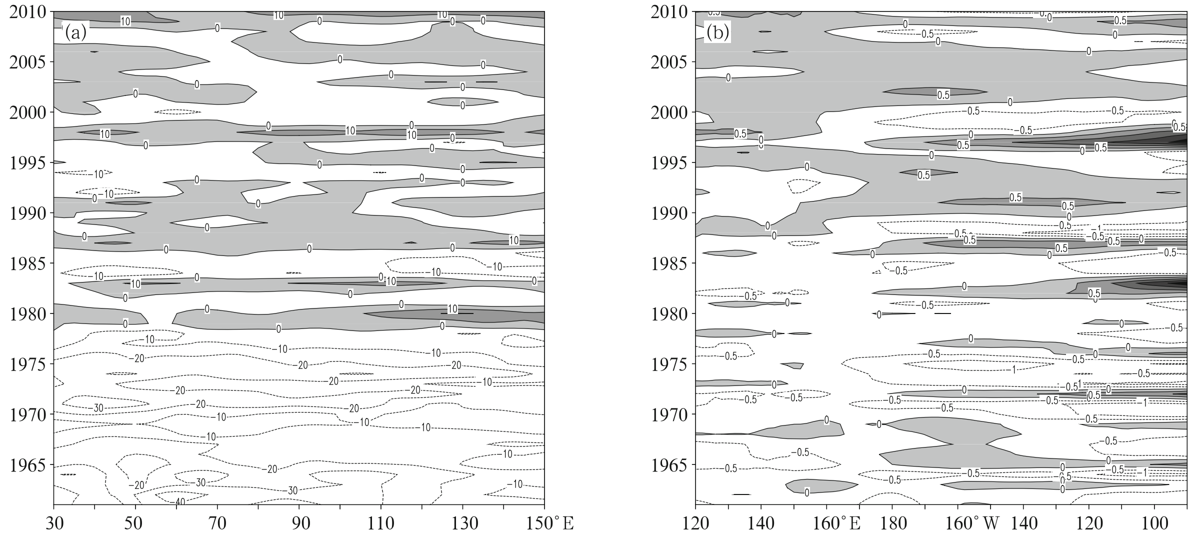

Fig. 1. Time-longitude cross-sections of (a) summer 500-hPa geopotential height anomaly along 20°–30°N and (b) summer SST anomaly along 10°S–10°N. Positive values are shaded.

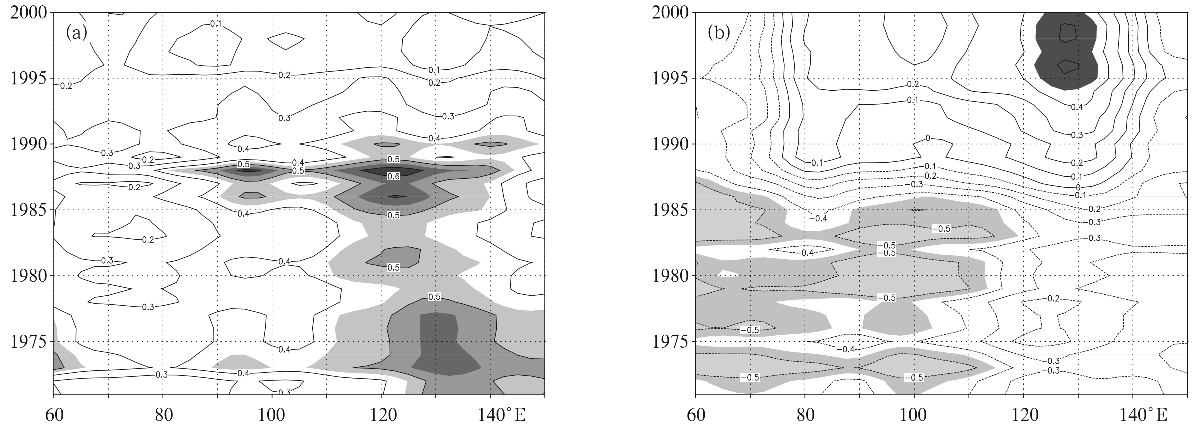

Fig. 2. 21-yr running correlation coefficients between the 500-hPa geopotential height averaged over 20°–30°N and the summer precipitation (a) along the Yangtze River and (b) in North China. The number on the ordinate gives the central year of the 21-yr running period (e.g., 1981 means the period 1971–1991). The number on the abscissa gives the longitude. Shaded areas imply the results significant at the 95% confidence level.

(CCs) between the 500-hPa geopotential height averaged over 20°–30°N and the summer precipitation along the Yangtze River and in North China. The decadal variations of their relationship are clearly revealed. Before the 1990s, precipitation along the Yangtze River had a significant positive correlation with the intensity of the WPSH (Fig. 2a), especially over 110°–140°E. This relationship is consistent with previous findings and has been applied in operational statistical climate prediction models (Zhao, 1999; Chen and Zhao, 2000). However, after the 1990s, the positive correlation weakened rapidly, especially in the 2010s when the CCs decreased to only about 0.1. This means that the WPSH had less direct impacts on the summer rainfall along the Yangtze River valley in this period, and this relationship became less important for forecasting. The weakened relationship can be attributed to the shift of the main rainfall belt in this period. It moves northward to the Huaihe River valley and to northern China, and the Yangtze River goes into its dry episode, whereas the WPSH exhibits a decadal strengthening trend (Zhao et al., 2008; Si et al., 2009, 2012).

On the other hand, in the recent two decades (2000s and 2010s), the relationship between the WPSH intensity and summer rainfall in North China shows a significant strengthening trend (Fig. 2b). Before the 1990s, the CCs were negative and the most significant negative center was located over the Indian Ocean. This is consistent with previous studies (Hao et al., 2011). In this period, negative CCs also appeared over western Pacific but did not exceed the 95% confidence level for Student's *t*-test (Zhang et al., 2008). After the 1990s, the negative correlation over the Indian Ocean decayed clearly, and the weak negative CCs over the western Pacific became significantly positive. As mentioned before, since the 1990s, above normal rainfall in North China always corresponds to a more westward and stronger WPSH. This correspondence is inconsistent with that assumed in traditional seasonal forecast models, but the results in Fig. 2 have confirmed existence of the inconsistency.

Similar to Fig. 2, Fig. 3 shows the 21-yr running CCs between the summer precipitation averaged at different latitudes in eastern China (east of 110°E) and the area index (Fig. 3a) and western boundary index (Fig. 3b) of the WPSH. These two indices represent the strength and position of the WPSH. Decadal changes can also be seen in Fig. 3. Before the 1990s, the area index had a significant positive relationship with the precipitation along the Yangtze River valley, but a weak and negative relationship with the precipitation in North China. The western boundary index also had a significant negative correlation with the precipitation along the Yangtze River valley, but a weak positive correlation with the rainfall in North China. The results indicate that before the 1990s, a more westward and stronger WPSH always led to more rainfall along the Yangtze River and less in South and North China, and vice versa.

However, decadal changes occurred in the recent two decades. The significant positive correlation between the WPSH area index and rainfall shifted from the Yangtze River to North China. Similarly, the significant negative correlation between precipitation and the western boundary index also moved northward. Note that in North China and northeastern China, the positive CCs before the 1990s became strongly negative. Though negative CCs still lay along the Yangtze River, their values decreased remarkably. Therefore, it can be concluded from Figs. 2 and 3 that the relationship between the WPSH and summer rainfall has undoubtedly changed.

Running correlations between the EASM index (Zhang et al., 2003a) and precipitation at each latitude in eastern China shows analogous changes. Figure 4 shows the weakening trend of the negative CCs between the EASM index and rainfall along the Yangtze River. The significant negative CCs before the 1990s validated the scenario used in traditional seasonal for-

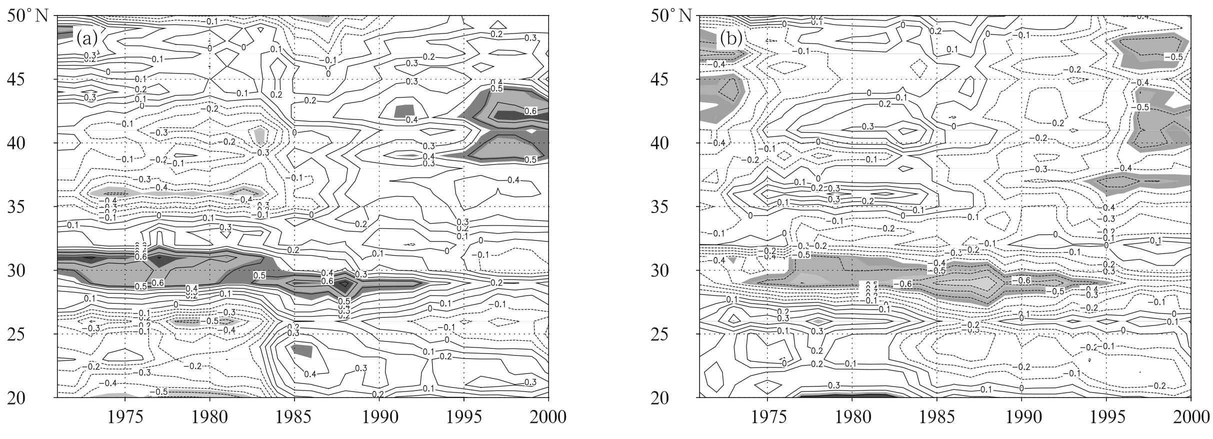

Fig. 3. 21-yr running correlation coefficients between the precipitation at each latitude in eastern China and the (a) area index and (b) western boundary index of the WPSH. The number on the abscissa gives the central year of the 21-yr running period. The number on the ordinate gives the latitude. Shaded areas imply the results significant at the 95% confidence level.

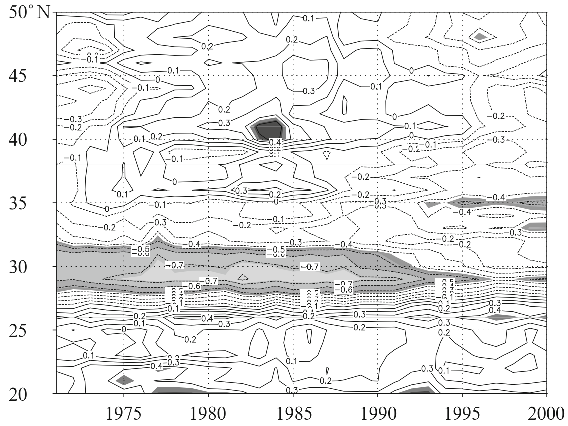

Fig. 4. As in Fig. 3, but for the CCs between rainfall and EASM index.

ecast models, namely, more (less) rainfall along the Yangtze River corresponds to a weaker (stronger) EASM. However, after the 1990s, the strong negative correlation weakened sharply. Another change occurred in northern China, especially in the regions north of 35°N, where the CCs changed from positive to negative. From Figs. 3 and 4, it can be concluded that the changed relationship between rainfall and the WPSH is consistent with the changed relationship between rainfall and the EASM.

In addition to the above-mentioned changed relationships, the summer rainfall in eastern China also experienced a changed relationship with the circulations in higher latitudes. Figure 5 shows the 21-yr running CCs between summer precipitation and the UBHI, BBHI, and OBHI, respectively. For the rainfall along the Yangtze River valley (red curves in Fig. 5), the UBHI and BBHI have more important impacts, especially the Baikal high. Their close relationships with summer rainfall were stable until around 1990. But during the 1990s and 2010s, the relationships weakened rapidly. For the precipitation in North China (black curves), the close negative relationship with the Ural high during 1960–1990 also weakened and became weak positive. This result supports the same conclusion on the changed relationship between rainfall and WPSH/EASM.

4. Possible explanation

Among the systems influencing the summer rainfall in China, the WPSH undoubtedly plays the most critical role. Its meridional position determines location of the interaction between warm and cold air masses, and its western boundary defines the transport path of the southwesterly monsoon moisture from ocean to continent. Due to global warming, SSTs have increased in most parts of the ocean, particularly in the western Pacific (figures omitted). The warm SSTs lead directly to the expansion of the atmospheric column and increase of the geopotential height, with a CC between the two fields above 0.4 as mentioned in Section 3. Figure 6 shows the 500-hPa geopotential height averaged between 20° and 30°N in each summer from 1961 to 2010. Obviously, the WPSH enhanced significantly and expanded westward since the 1980s, especially over the most recent two decades. In some years such as 1998 and 2010, the western boundary of the WPSH even reached the eastern part of the East Asian continent.

As mentioned earlier, both the shape and intensity of the WPSH can cause differences in the moisture transport path and strength, and finally alter the location of the Meiyu rainfall belt. For summer rainfall in eastern China, two moisture transport channels ex-

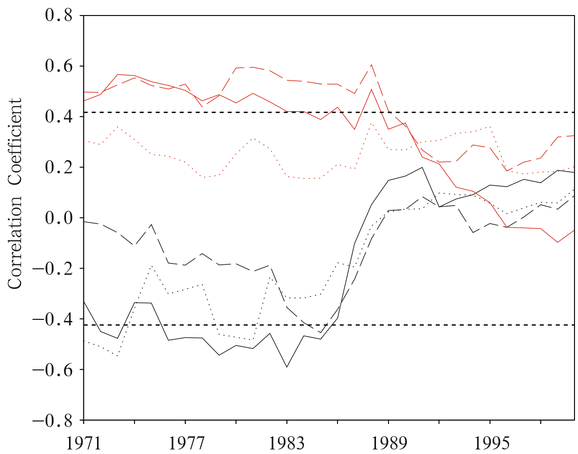

Fig. 5. 21-yr running CCs between summer precipitation and the UBHI (solid curves), BBHI (thin dashed curves), and OBHI (dotted curves), respectively. Red lines show the precipitation along the Yangtze River and black lines show the precipitation in North China. The number on the abscissa means the central year of the 21-yr running period. Thick dashed lines mean the 95% confidence level.

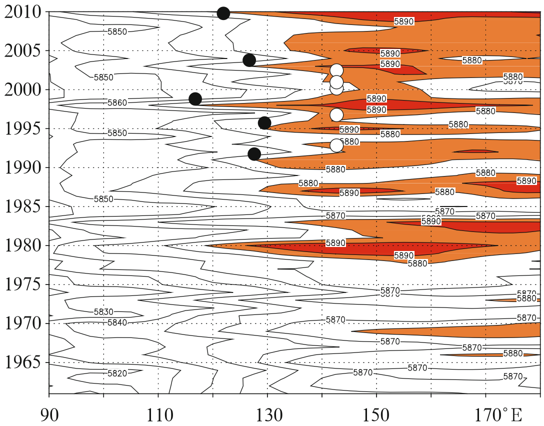

Fig. 6. 500-hPa geopotential height averaged between 20° and 30°N in each summer from 1961 to 2010. Values greater than 5880 gpm are shaded. The open and filled circles mean the five weaker and stronger WPSH cases studied in this paper.

ist. The first channel is via the southwesterly from the Arabian Sea and the Bay of Bengal, and the second is via the southeasterly from the western Pacific. Both channels relate closely to the WPSH. For example, a stronger southwest monsoon can propel the subtropical high to be further eastward and weaken its strength, and thus alter the moisture transport path and intensity of the southeast monsoon, and vice versa (figures omitted).

For composite analysis, five stronger and five weaker WPSH cases during 1991–2010 are chosen as shown in Fig. 6. The stronger WPSH cases occurred in 1991, 1995, 1998, 2003, and 2010; while the five weaker WPSH cases occurred in 1992, 1997, 1999, 2000, and 2002. The composite 850-hPa wind and 500-hPa geopotential height are displayed in Fig. 7. A remarkable expansion of the WPSH appeared in the recent two decades. In comparison to the climatology of 1981–2010, the western boundary of the 5880-gpm contour in the stronger WPSH years extended to 120°E. The southerly components of both the southwesterly monsoon on its western side and the southeasterly monsoon on its southern side are much stronger in the stronger WPSH cases than their counterparts in the weaker WPSH cases. Therefore, in stronger WPSH years, the moisture over the South China Sea and the western Pacific could be transported more directly to the continent. The southerly wind speed maximum is located along the Yangtze River, so moisture at lower levels converges in the regions north of the river. This explains why a stronger WPSH brings more rainfall to northern China instead of to the Yangtze River in the recent two decades. It also confirms the conclusion by Zhang (1999) that the water vapor condition in North China is closely related to the intensity of the southerly monsoon in East Asia.

However, the circulations in the weaker WPSH cases display an asymmetric feature owing to the decadal enhancement of the WPSH. Composite results indicate that the WPSH is not more eastward than its climatology. Under this pattern, abundant moisture cannot be easily brought to the Yangtze River. Distinct differences in moisture transport between the stronger and weaker WPSH cases occurred over the tropical western Pacific, i.e., east of 120°E. In these regions, the zonal wind directions differ almost 60 degrees in the two WPSH cases (stronger vs. weaker; See Fig. 7). However, over the regions west of 120°E, the wind directions are almost the same although their speeds are different. This indicates that the WPSH plays a more important role in changing the relation-

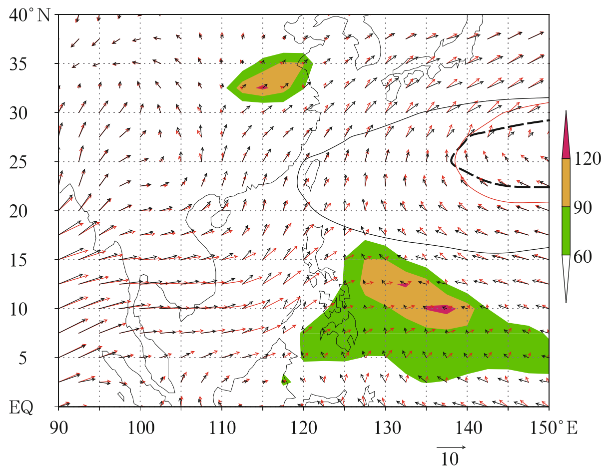

Fig. 7. Composite of the 850-hPa wind (arrows) and 5880-gpm contours of the 500-hPa geopotential height in the stronger (black) and weaker (red) WPSH cases. The thick dashed contour is the climatology. Shaded areas indicate that the mean differences of wind directions between the two cases are greater than 60°.

ships between the WPSH/EASM and rainfall in recent decades. This result also agrees with the conclusion by Liu and Ding (2011) that the moisture is mainly transported from the west and south sides of North China to cause flood events in the region.

5. Conclusions and discussion

The EASM circulations exert large influences on the summer rainfall in China. Their close relationships have been widely used in operational prediction of short-term climate in China. In traditional statistical forecast models, a La Niña event (i.e., lower SSTs in the equatorial eastern Pacific) is assumed to cause a weakened and more northward WPSH and stronger summer monsoon, and finally brings floods to northern China and drought along the Yangtze River; on the other hand, a stronger and more southward WPSH, weaker monsoon, and more active blocking highs will together induce floods along the Yangtze River.

However, obvious changes occurred over the recent two decades (after the 1990s). The relationships between EASM circulations and rainfall in eastern China have all changed remarkably. For example, before the 1990s, precipitation along the Yangtze River had a significant positive correlation with the intensity of the WPSH, but after that the positive correlation weakened rapidly. In the same period, the CCs between summer rainfall in North China and the WPSH also changed from weakly negative to significantly positive. These changes present a big challenge to the application of the traditional seasonal forecast model.

The asymmetric features of the monsoon circulations in stronger and weaker WPSH cases during 1991–2010 may cause this change. In this period, owing to global warming, the mean western boundary of the WPSH in stronger years can extend quite far westward to 120°E. The southwesterly monsoon on the western side of WPSH is much stronger, especially the meridional component. More moisture over the South China Sea and the western Pacific is transported directly to the regions north of the Yangtze River valley, i.e., North China, to form a region of convergence. More summer rainfall is then found in northern China instead of along the Yangtze River. Meanwhile, in weaker WPSH cases, the western boundary of the WPSH is near its climatology around 140°E. Above normal rainfall cannot be easily brought to the Yangtze River valley. It could be concluded that the WPSH plays a more important role in changing the relationships between WPSH/EASM and rainfall in eastern China in the recent two decades.

Previous studies considered that an El Niño event would lead to a stronger WPSH, such as in 1998, while a La Niña event would result in a weaker WPSH. We also conducted a preliminary analysis to explore the changed relationship between ENSO and the WPSH in the recent two decades (figures omitted). The increased frequency of the central Pacific-type ENSO may possibly alter the traditional relationship. Therefore, it is also necessary to analyze the roles of ENSO in changing the relationship between monsoon circulations and summer rainfall. This will be conducted possibly in a future study.

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