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Precipitation seesaw phenomenon and its formation mechanism in the eastern and western parts of Northwest China during the flood season

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Abstract Extending across three major plateaus, namely the Qinghai-Tibetan Plateau, the Inner Mongolia-Xinjiang Plateau and the Loess Plateau, Northwest China has the complex terrain and spatio-temporal climate variations, and is affected by the interactions among different circulation systems, such as the summer monsoon, the westerlies and the plateau monsoon. The understanding of the climate variability, as well as its characteristics and evolution mechanisms in this area has been limited so far. In this paper, the precipitation characteristics and mechanisms in the eastern and western parts of Northwest China during the flood season are compared and analyzed based on the data from 192 national meteorological observational sites in Northwest China in 1961–2016. The results show that, divided by the northern boundary of the East Asian summer monsoon, there are huge differences in the precipitation variation characteristics between the eastern and western parts. The inter-annual variations, inter-decadal variations and total trends in the two parts all show a significant seesaw phenomenon. Moreover, it is found that the seesaw phenomenon of precipitation variation is closely related to the opposite variation between the East Asian summer monsoon index (MI) and the westerly circulation index (WI). In addition, the inverse variations on different time scales are only related to the contributions of precipitation at specific grades. Besides, in the two matching patterns of precipitation in the seesaw phenomenon, the middle and high latitudes are occupied by the "high-low-high" wave trains in the precipitation increases in the east of Northwest China (ENWC) and decreases in the west of Northwest China (WNWC) pattern, meaning precipitation increases in ENWC and decreases in WNWC. Whereas the opposite "low-high-low" wave trains at 500 hPa height are observed in the middle and high latitudes in the WH-EA pattern at 500 hPa height, meaning precipitation increases in WNWC and decreases in ENWC. Thus, the atmosphere circulation situation with two wave train types can support both the precipitation seesaw phenomenon and the opposite variation between MI and WI. Moreover, the seesaw phenomenon is shown to be related to the separate or joint effects of the South Asian High, ENSO and the plateau heating on the common but opposite effect on the summer monsoon and the westerlies, in which the South Asian High probably plays a more critical role. This study could deepen the scientific understanding of precipitation mechanisms and improve the weather forecast technology in Northwest China during the flood season.

Keywords Northwest China, Precipitation changes, Seesaw phenomenon, Summer monsoon system, Westerly circulation system, South Asian High

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1. Introduction

Northwest China (NWC) is an inland region located between 33°N and 45°N (Zhang et al., 2000), spanning three major plateaus, i.e. the Qinghai-Tibetan Plateau, the Inner Mongolia-Xinjiang plateau and the Loess Plateau. It has complex terrain and various types of climate, and is the region with the biggest allobaric difference between winter and summer in China. The seasonal distribution of precipitation has both single-peak type and double-peak type, and the precipitation characteristics of the East China, Qinghai-Tibet Plateau and Xinjiang can be found in this region. In general, the spatial precipitation distribution in NWC is non-uniform, with total precipitation decreasing from southeast to northwest. The mean annual precipitation in the southeastern part of the region is higher than 1000 mm. Even in Qilian Mountains and the Tianshan Mountains in its west, the precipitation can reach about 800 mm. But in Toksun, its westernmost part, the mean annual precipitation is only 6.4 mm. In the hinterland of the Taklimakan Desert, almost no precipitation occurs all year round. Therefore, not only the spatial gradient of precipitation in this area is very large, reaching 1.5 mm km^{-1} in the central and southern part of Gansu Province (Bai et al., 1988), but the coefficient of variation (the standard deviation of precipitation sequence in 1961–2016 divided by the mean in the same sequence) of precipitation is also very high, ranging from 20% to 50% in most regions and more than 90% in the Ruoqiang region on the southeastern edge of the Taklimakan desert.

In terms of the atmospheric circulation system, the climate in China is mainly affected by the monsoon circulation system, the westerly circulation system and the plateau circulation system. The regions affected by the large circulation systems are mainly determined by the location of the northern fringe of East Asian summer monsoon (EASM). In general, the southeast side of the line is controlled by the summer monsoon circulation system, while its northwest side is controlled by the westerlies circulation system, and its southwest side is affected by the plateau circulation system. NWC extends across the northern fringe of EASM (Huang et al., 2009; Li et al., 2013; Chen et al., 2018; Liu et al., 2018), and a number of areas are in the summer monsoon transitional zone, thus the weather and climate are influenced by the EASM system, the westerly weather system and the plateau weather system. The precipitation of the whole year is mainly concentrated in the flood season from May to September, and the other months are basically dry. During the flood season, the precipitation in the east of Northwest China (ENWC) is mainly affected by the EASM, whereas the precipitation in the west of Northwest China (WNWC) by the westerlies and precipitation in the south of NWC by the plateau monsoon (Wang et al., 2004). Some regions may even be affected by the alternation or superposition of these three circulation systems. Under the background of global warming, the atmospheric circulation is also undergoing obvious adjustment, causing the changes of the EASM circulation and the westerlies circulation (Wang, 2001, 2002). In fact, the location of the EASM north edge in recent decades has changed obviously (Li et al., 2013; Zhang et al., 2017), and the climate distribution pattern in China is also undergoing profound changes (Wei et al., 2003; Yang et al., 2003; Lin and Zhang, 2015a, 2015b). NWC is located at the interchanges of the EASM, the westerly zone and the plateau monsoon, thus almost any adjustment of the circulation system in the East Asian region will cause a climate change in this region. Therefore, the precipitation in flood seasons will be more sensitive to the adjustment of atmospheric circulation caused by global warming in this region (Li et al., 1997; Shi et al., 2002; Zhang et al., 2003). It can be seen that the atmospheric circulation characteristics affecting the weather and climate in NWC are quite unique, and the influencing factors of precipitation in flood seasons are also quite complex. Therefore, the forecast of precipitation in flood seasons in this area remains a significant problem.

Previous studies have shown that (Wang et al., 2004; Zhao et al., 2006; Chen and Huang, 2012; Chen and Zhai, 2014; Yuan et al., 2015; Li et al., 2013; Liu et al., 2017) the flood season precipitation anomaly in NWC is closely related to the variation and adjustment of the circulation factors such as the EASM circulation and its northern edge, the westerlies and polar vortex, especially to the Indian summer monsoon. There are obvious regional differences in precipitation due to the influence of circulation systems. It is noteworthy that for nearly half a century, the precipitation and the number of rainy days in ENWC in flood seasons have been decreasing (Bai et al., 2005; Chen and Dai, 2009; Guo et al., 2009; Yao et al., 2017), while the precipitation in WNWC has been increasing (Lin and Zhang, 2016). Moreover, some studies have also preliminarily suggested that the difference and the correlation features between the precipitation trends in ENWC and WNWC during the flood season are probably related to the interactions among the summer monsoon weather systems, the westerlies and the plateau weather systems (Zuo et al., 2004). From the paleoclimate study, An et al. (2012) also found that the westerly climate and the Asian summer monsoon climate often showed opposite variations on the millennial time scale of the glacial-interglacial period, in which the westerly climate dominated in the glacial period, while the Asian summer monsoon climate dominated in the Holocene period. The difference was related to the regulation of the high latitude ice sheet and solar activity, sea surface temperature of the north Atlantic and the low latitude ocean. However, for a long time, there have been neither studies giving the clear relationship between the precipitation trends in ENWC and WNWC during the flood season, nor many studies on how the relationship between regional precipitation trends is affected by different time scales and different grades of precipitation. In particular, the influence mechanism of atmospheric circulation on the regional precipitation variation in this area has hardly been involved in past studies.

In view of this, this paper aims at clarifying the different precipitation trends of ENWC and WNWC in flood seasons based on the comparison of the precipitation variations on different time scales in these two areas. The precipitation variation trends and their relationship with time scale and precipitation intensity are analyzed in this paper. The influence mechanisms of the main circulation factors, such as the EASM circulation and the westerly circulation, on the difference of the precipitation variation trend in ENWC and WNWC in flood seasons are studied. Besides, the relationships between the variation and adjustment of the EASM circulation as well as the westerly circulation and the South Asian High and El Niño/Southern Oscillation (ENSO) are also discussed. Therefore, this paper could provide new information for the precipitation prediction, diagnosis and analysis of drought/flood in NWC in flood seasons.

2. Data and methods

2.1 Research area

As shown in Figure 1, the research area is 75°E–111°E and 32°N–49°N, including the administrative regions of Shaanxi, Gansu, Ningxia, Qinghai and Xinjiang. For simplicity, the area with an elevation over 3500 m is excluded as the plateau climate system. Considering that the climate of China is mainly affected by the EASM and westerly circulation systems, the ENWC and WNWC are bounded by the multi-year averaged north fringe of EASM (Hu and Qian, 2007; Li et al., 2013; Zhang, 2018). The southeast side of it is defined as the ENWC, and the northwest side of it the WNWC. Figure 1 shows that the annual precipitation tendency in ENWC is basically negative, while that in WNWC is basically positive. It indicates that this zoning method is relatively reasonable.

2.2 Data

The precipitation data of 258 stations in NWC used in this paper is provided by the National meteorological information of the China Meteorological Administration, and it is mainly the daily observation data from May to September of 1961–2016. The data of 192 stations is used in the actual research after excluding data from the stations with no measurement over 5 days, to make sure that the observed data is representative. Moreover, the daily precipitation less than 0.1 mm is not counted as rainy days to exclude the influence of invalid precipitation. Due to the large spatial precipitation difference in NWC and the need to analyze the influence of precipitation in different grades, we have redefined 21 different-class precipitation (Table 1) based on the precipitation grade standard proposed by China Meteorological Administration (China Standard Press, 2012).

The geopotential height field, zonal wind, radial wind and vertical velocity data used in this paper are derived from the National Centers for Environmental Prediction (NCEP)/the National Center for Atmospheric Research (NCAR) reanalysis dataset.

2.3 Methods

At present, there are many indexes representing the activity of the EASM (Yim et al., 2014). The index established by Wang and Fan (1999) is used to define the summer monsoon by using the mean zonal wind difference at 850 hPa between the regions of (5°N–15°N, 90°E–130°E) and (22.5°N–32.5°N, 110°E–140°E). The formula is as follows:

$$\begin{aligned}\mathrm{MI} = {} & U_{850}[5°\,\mathrm{N}-15°\,\mathrm{N}, 90°\,\mathrm{E}-130°\mathrm{E}] \\ & -U_{850}[22.5°\,\mathrm{N}-32.5°\,\mathrm{N}, 110°\,\mathrm{E}-140°\mathrm{E}],\end{aligned} \tag{1}$$

where, MI is the index of EASM activity, and U is mean zonal wind at 850 hPa, with a unit of m s^{-1}.

The index in this paper is the same as Li et al. (2008). The WI is defined by the difference of the mean zonal height at 500 hPa between 35°N and 50°N in 70°E–110°E. The formula is as follows:

$$\mathrm{WI} = \frac{1}{17}\left[\sum_{\lambda=1}^{17} H(\lambda, 35°\mathrm{N}) - \sum_{\lambda=1}^{17} H(\lambda, 50°\mathrm{N})\right], \tag{2}$$

where, H is the mean zonal height at 500 hPa along the 35°N and 50°N, with a unit of gpm. λ is the number of longitudes determined along the zonal circle with an interval of 2.5°.

In addition, the main analytical methods in this paper are correlation analysis method and linear tendency method. The linear regression coefficient (i.e. tendency rate) is obtained by least square estimation, and the correlation coefficient r between time and variable is also obtained. Then the significant criterion R_a is determined according to the reliability level α. If $R>R_a$, the variation of variables with time is significant (Wei, 2007). The length of the data is 56 years. Using a confidence level of 95% (i.e. α=0.05), R_a equals 0.26; while using a confidence level of 99% (i.e. α=0.01), R_a equals 0.34.

In order to distinguish the matching characteristics of precipitation variation between ENWC and WNWC during the flood season, the matching relationships can be classified into four types. The WA-EH type means precipitation increases in ENWC and decreases in WNWC, while the WH-EA type is the opposite. The WH-EH type and WA-EA type respectively indicate that the precipitation increases and decreases simultaneously in ENWC and WNWC.

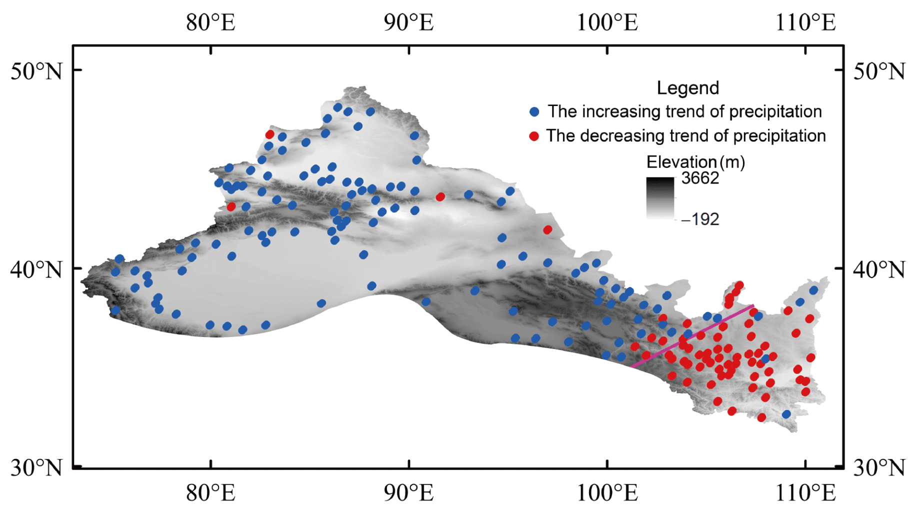

Figure 1 Regional division of ENWC and WNWC and the precipitation tendency distribution of stations in the same period.

Table 1 Classification of rainfall grades

Light rainfall grade		Moderate rainfall grade		Heavy rainfall grade		Rainstorm grade		Heavy rainstorm grade	
Rainfall grade	Precipitation (mm)	Rainfall grade	Precipitation (mm)	Rainfall grade	Precipitation (mm)	Rainfall grade	Precipitation (mm)	Rainfall grade	Precipitation (mm)
1	0–1	5	10–15	8	25–30	13	50–60	18	100–120
2	1–2.5	6	15–20	9	30–35	14	60–70	19	120–150
3	2.5–5	7	20–25	10	35–40	15	70–80	20	150–200
4	5–10			11	40–45	16	80–90	21	200–300
				12	45–50	17	90–100		

3. Seesaw phenomenon of precipitation variation between the east and west of Northwest China during the flood season

To compare the precipitation variation differences between ENWC and WNWC in flood seasons systematically, the general trends of precipitation anomaly percentage in ENWC and WNWC, 7-year sliding average curve of precipitation anomaly percentage and the comparison of inter-decadal climate tendency rate of precipitation in different periods are given in Figure 2. Figure 2a shows a precipitation anomaly percentage increasing trend in WNWC in flood seasons with a climatic tendency rate about 3.5% $(10\ \mathrm{yr})^{-1}$, this result is credible as it has passed the significant test of 0.01. While it shows a precipitation anomaly percentage decreasing trend in ENWC in flood seasons with a climatic tendency rate about −1.3% $(10\ \mathrm{yr})^{-1}$, but this result does not pass the significance test. Moreover, the precipitation trends in ENWC (−5.3% $(10\ \mathrm{yr})^{-1}$) and WNWC (4.8% $(10\ \mathrm{yr})^{-1}$) in flood seasons are opposite in general.

The 7-year sliding average curve of precipitation anomaly percentage in Figure 2b further shows a general opposite variation of the quasi-periodic fluctuation process of precipitation in ENWC and WNWC in flood seasons. The precipitation variation in the recent 50 years in NWC could be divided into five periods: 1961–1969, 1969–1982, 1982–1998, 1988–2011 and 2011–2016. From the precipitation trends in ENWC and WNWC during the flood season in these five periods, it is found that the WA-EH type and the WH-EA type have appeared many times. Basically the WH-EH type and the WA-EA type have rarely appeared. In Figure 2b, the fluctuation characteristics of the 7-year sliding average curve basically reflect the decadal variation characteristics of precipitation in ENWC and WNWC during the flood season. The correlation coefficient of 7-year sliding average sequence of precipitation anomaly percentage between ENWC and WNWC in flood seasons is –0.2830, passing the significant test of 0.05. The comparison of climatic tendency rates between ENWC and WNWC during the flood seasons in the five periods in Figure 2c shows that in these periods on the inter-decadal scale, the climatic tendency rates of precipitation anomaly percentage in both ENWC and WNWC show a relation of inverse matching, just different in degrees.

So as to determine whether the total precipitation trends and the total opposite variation change on the inter-decadal scale in ENWC and WNWC will appear on the inter-annual scale, Figure 3 presents the comparison of the annual pre-

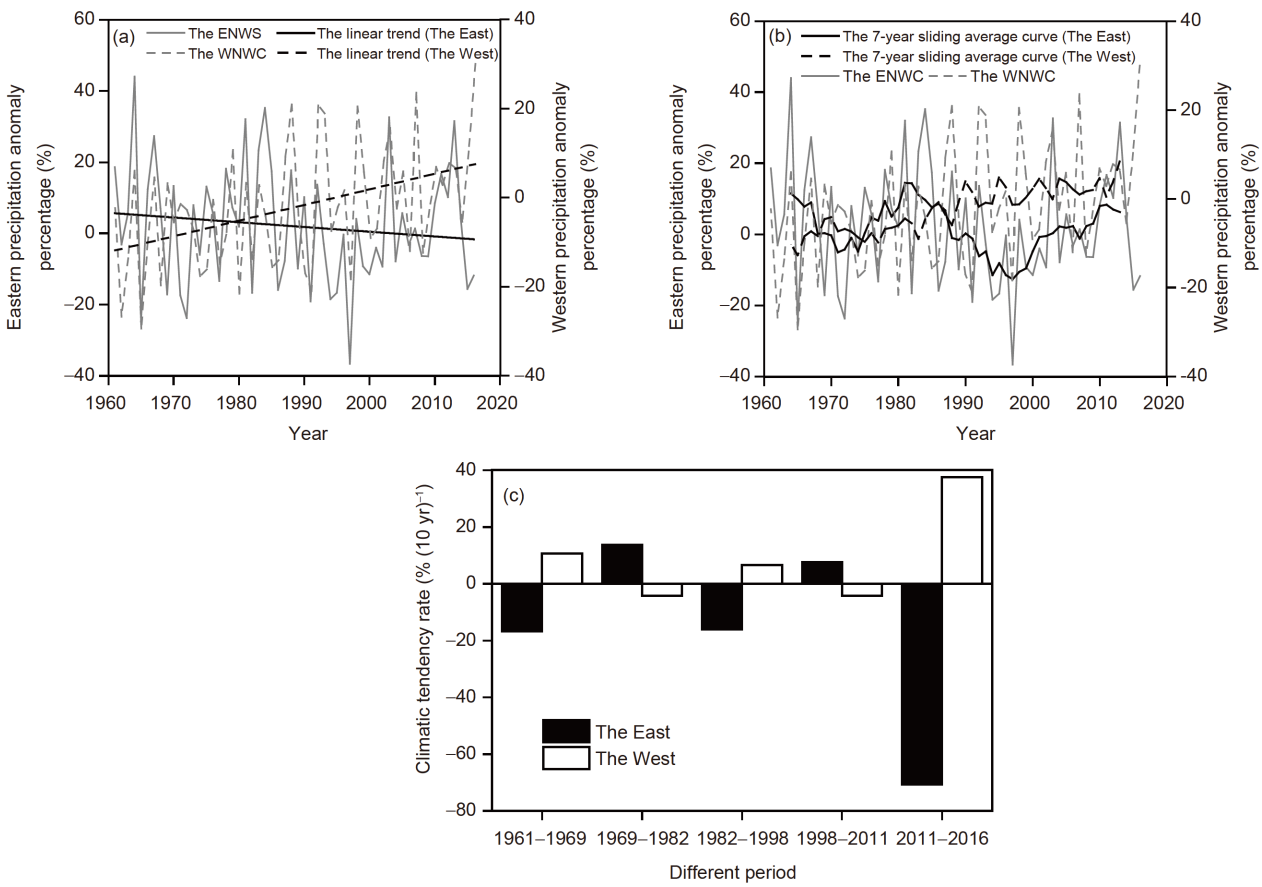

Figure 2 Variation of precipitation anomaly percentage in ENWC and WNWC during flood season from 1961 to 2016. (a) Annual change; (b) 7-year sliding average curve; (c) the tendency distribution at different periods.

cipitation anomaly distributions between ENWC and WNWC, and the comparisons of the occurrence frequency in three precipitation anomaly matching patterns between ENWC and WNWC. In Figure 3b, we only count the precipitation anomaly with an absolute value greater than 5% as a positive anomaly or a negative one. The three precipitation anomaly matching types are as follows: (1) opposite anomalies between ENWC and WNWC, (2) positive anomalies in both ENWC and WNWC, and (3) negative anomalies in both ENWC and WNWC. As can be seen from Figure 3a, the precipitation anomalies in ENWC and WNWC were mostly opposite in the past half century, although the variation of precipitation anomaly in ENWC was larger than that in WNWC. Furthermore, in Figure 3b, the statistical comparison of the different precipitation anomaly frequency matching types in ENWC and WNWC in flood seasons shows that the first type is of the largest probability (42.4% of the total number of years), the second type comes 30.3% and the third type comes 27.3%. It indicates that even on the inter-annual time scale, the opposite variation of the precipitation between ENWC and WNWC is also prominent.

In a word, it is plain that there is a seesaw phenomenon about the precipitation between ENWC and WNWC, according to the comparison between the precipitation changes in these two areas on different time scales, including the reverse trends on the long time scale, the inverse phase change on the inter-decadal time scale and the dominant inverse anomaly matching type on the inter-annual scale.

4. Influence of different grades of precipitation on seesaw phenomenon variation

The precipitation seesaw variation in ENWC and WNWC is related to the adjustment or transformation of precipitation distribution patterns. However, it requires further research to find out which grade of precipitation contributes to the precipitation seesaw variation in ENWC and WNWC in flood seasons. Therefore, the climatic tendency distribution of the precipitation and rainy days of different grades of precipitation in ENWC and WNWC are given in Figure 4. It can be seen that the climatic tendency rates of precipitation below 10–15 mm are negative in both ENWC and WNWC, while those with the precipitation above 80–90 mm are positive. It indicates that the precipitation of smaller grades is decreasing, and that of larger grades is increasing. The dif-

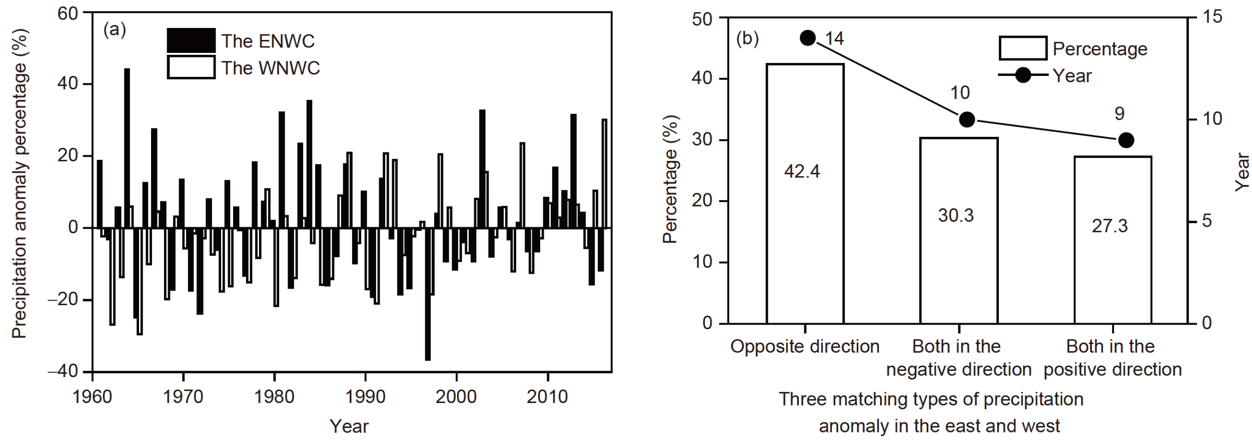

Figure 3 Variation of precipitation (a) and its frequency comparison of three matching types (b) in ENWC and WNWC during the flood season from 1961 to 2016.

ference of precipitation climatic tendency rate between ENWC and WNWC mainly appears in the 15 to 80 mm range, in which the eastern precipitation climatic tendency rates are basically negative, while the western precipitation climate tendency rates are basically positive. It indicates that the precipitation seesaw phenomenon in WNWC in flood seasons is mainly caused by the contribution of the ten rainy grades (15 to 80 mm).

So as to further understand the contribution of different-grade precipitation on inter-decadal time scale to the precipitation seesaw variation in ENWC and WNWC during the flood season, the four relatively complete inter-decadal periods need to be divided into the WA-EH type and the WH-EA type for comparative analysis. In Figure 5, the different distributions of different-class precipitation and rainy days between two types are given. It is obvious that the precipitation differences between the WA-EH type and the WH-EA type are basically positive in WNWC and negative in ENWC when the precipitation is less than or equal to the grade of 60–70 mm, but the differences are positive in ENWC and not obvious in WNWC when the precipitation is over 60–70 mm. It indicates that when the precipitation is 60–70 mm or less, the precipitation increases in WNWC and decreases in ENWC during the transition from the WA-EH type to the WH-EA type. But when the precipitation is above 60–70 mm, it increases obviously in ENWC and it keeps stable in WNWC.

Theoretically, to realize the transition from the WA-EH type to the WH-EA type, the precipitation must increase in WNWC and decrease in ENWC. It can be inferred that the shift from the WA-EH type to the WH-EA type is mainly caused by the precipitation variation of grade 60–70 mm or lower. That is to say, the maintenance of seesaw phenomenon in ENWC and WNWC is mainly due to the precipitation from light rainy grade to low-intensity rainstorm, rather than the strong grades. The difference of rainy days between the WA-EH type and the WH-EA type generally decreases, indicating that the precipitation of high-intensity storm (equal or above 100 mm) in ENWC and WNWC generally increases during the transition from the WA-EH type to the WH-EA type, while the numbers of the rainy days still decrease. Therefore, the precipitation extremes in NWC will be intensified.

5. Relationship between summer monsoon circulation and westerly circulation and the precipitation seesaw variation in Northwest China

It is well known that China is in the monsoon climatic region, and its precipitation distribution pattern is mainly controlled by the EASM circulation (Wang, 2001; Yim et al., 2014). However, the westerly circulation is an important link between the Atlantic climatic region and the Asian climate, which controls the region outside the north boundary of the East Asian monsoon to some extent. And it affects the climate of the Asian monsoon region and even the globe by interacting with the Qinghai-Tibet Plateau (Yan et al., 2007). Some studies suggested that during glacial-interglacial cycles, the severe changes of the position and intensity of the westerly circulation can hugely affect the East Asian monsoon climate and the global climate, and they are of great significance to both the monsoon precipitation and the westerly precipitation (Qu et al., 2004). Therefore, the influence of westerly circulation on precipitation and climate in China cannot be ignored.

For NWC, many studies have shown that (Li et al., 2003; Zhang et al., 2003; Wang et al., 2004; Li et al., 2008) the westerly circulation provides a basic source of water vapor for WNWC, whereas the EASM directly affects ENWC through the atmospheric water vapor transport by southwest and southeast airflow. Therefore, the climate in NWC is actually the result of the alternation or superposition of the westerly circulation at the planetary scale, the subtropical circulation at the intercontinental scale and the plateau cir-

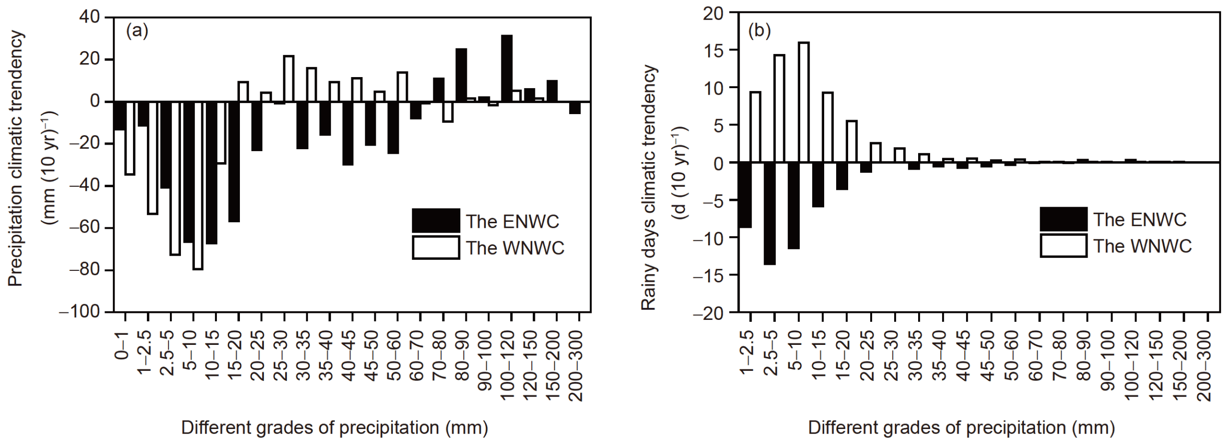

Figure 4 Climatic tendency distribution of precipitation (a) and rainy days (b) under different rainfall grades in ENWC and WNWC.

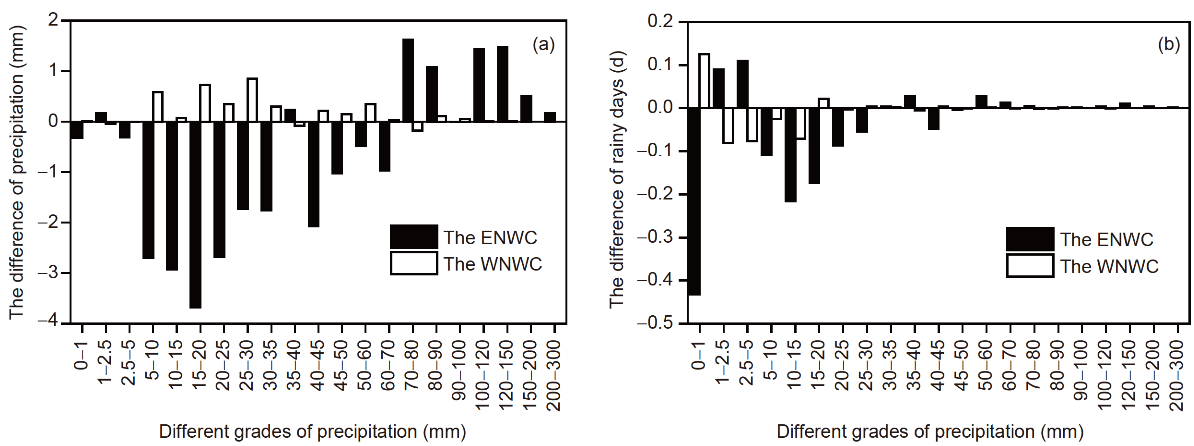

Figure 5 Difference distribution of precipitation (a) and rainy days (b) in ENWC and WNWC under the WA-EH style WH-EA style.

culation at the regional scale. In particular, the alternating influence of westerly circulation and EASM may have become the most important climatic situation for NWC since the Quaternary. In general, the EASM dominates the precipitation in ENWC, while the westerly circulation dominates the precipitation in WNWC. For this reason, the precipitation seesaw phenomenon in ENWC and WNWC can be attributed to the adjustment of the EASM circulation and westerly circulation. In view of this, the general trend of the MI and the WI, 7-year sliding average curve and the comparison of climatic tendency rates of the MI and the WI distribution are given in Figure 6. In Figure 6a, the MI generally decreases, while WI generally increases, and the correlation coefficient of 7-year sliding average sequence of the MI and WI is −0.1587, which does not pass the significance test. It is similar to the precipitation seesaw variation in ENWC and WNWC in Figure 2, where the MI and the WI show a seesaw variation, but it seems less significant than that in the precipitation. Figure 6b and 6c further indicate that the changes in the MI and WI are featured by the opposite variation on the inter-decadal scale. During 1961–1969 and 1969–1982, the opposite variation was particularly obvious. So was the climate tendency, which was opposite in these two periods.

Similarly, the annual variation of MI anomaly and WI anomaly, and the comparisons of the occurrence frequency in three matching types of MI and WI anomalies are given in Figure 7, in order to further understand the inter-annual variation of MI and WI. We only count the anomaly with an absolute value greater than 0.05 as a positive or negative anomaly in Figure 7b. The three matching types of index anomaly include: (1) opposite anomalies in MI and WI; (2) negative anomalies in both MI and WI; and (3) positive anomalies in both MI and WI. It can be seen from the figure that the MI anomaly is opposite to the WI anomaly in most cases on the inter-decadal scale, that is, if the MI anomaly is positive, the WI anomaly will be negative, and *vice versa*. Statistics for all years also show that the MI anomaly is opposite to that of the WI for 52% of the years (26 years), while the years that MI anomaly and the WI anomaly are both negative account for 26%, both positive for 22%. It is obvious that the MI and the WI have obvious seesaw char-

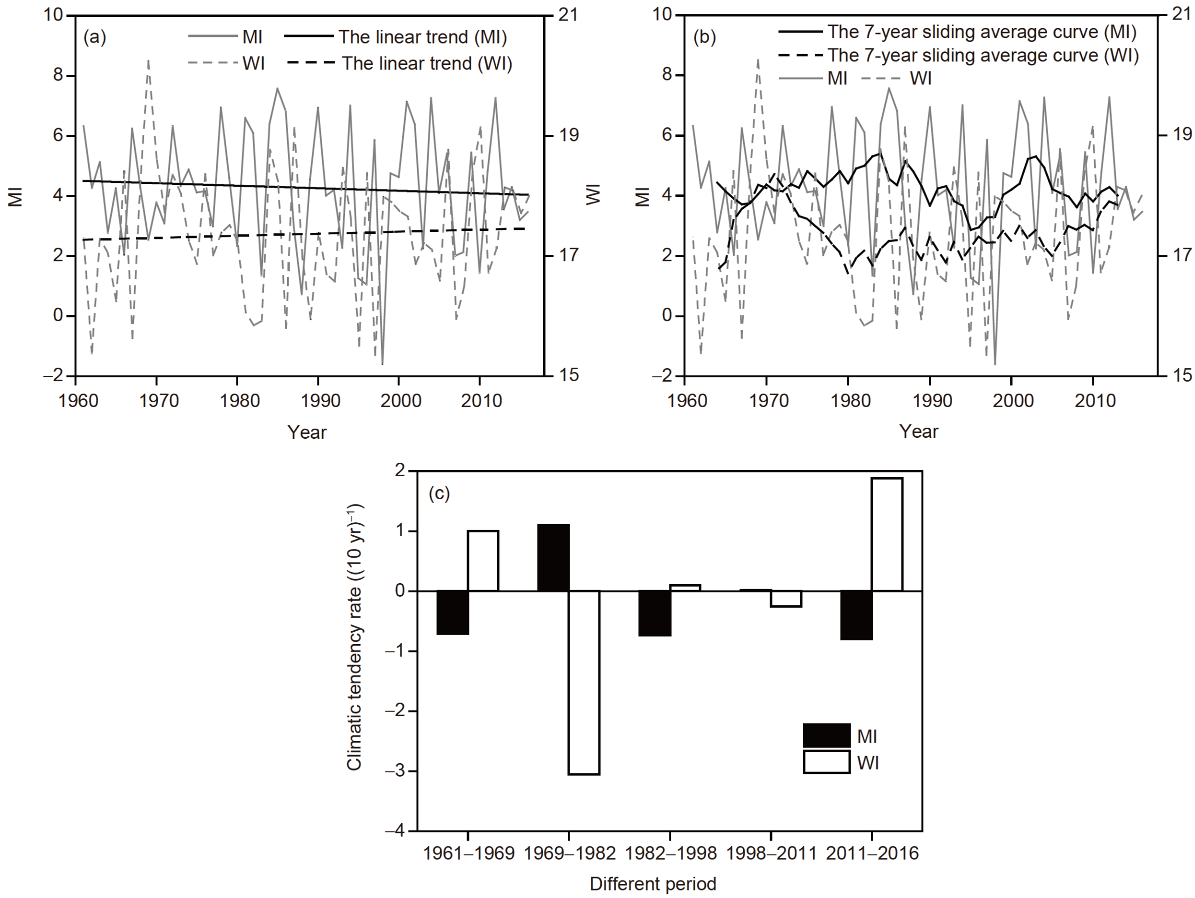

Figure 6 Variation of MI and WI from 1961 to 2016. (a) Annual change; (b) 7-year sliding average curve; (c) the tendency distribution at different periods.

acteristics even on the inter-annual scale.

It can be seen from the above analysis that the MI and the WI present seesaw variations, which is similar to the precipitation variations in ENWC and WNWC. To better understand the correlation between the precipitation variations in ENWC and WNWC and the EASM and westerly circulation, Figure 8 gives the comparison of the eastern precipitation variation trend and the MI variation and the comparison of the western precipitation variation trend and the WI variation. It is clearly shown that the precipitation in ENWC during the flood season is positively correlated with the MI, and the correlation coefficient is 0.5447. It has passed the significance test of 0.01, and the correlation coefficients are 0.7743 and 0.8538 in 1969–1982 and 1982–1998, respectively.. The precipitation in WNWC is positively correlated with the WI, but does not pass the significance test. The correlation coefficient of which is 0.8875 during 1964–1969, and pass the 0.05 significance test. Moreover, the correlation is that the precipitation in ENWC increases when the EASM increases, and the precipitation in WNWC increases when the WI increases (image omitted). The above analyses show that the seesaw variation in ENWC and WNWC is mainly related to the opposite variation of the MI and the WI.

6. The influence mechanism of circulation on the precipitation seesaw variation

Both the seesaw phenomenon in ENWC and WNWC and the inverse variations of MI and WI are related to the change and adjustment of the general circulation situation. Figure 9 shows the 500 hPa geopotential height field for the WA-EH type and the WH-EA type. As can be seen from Figure 9, the WA-EH type and the WH-EA type are quite different. In the middle and high latitudes of the WA-EH type, the "high-low-high" wave train is formed. The NWC is controlled by a high pressure, which is bad for the cold air to advance southward. The pressure is low in the west, and high in the east in China. The ENWC is mainly controlled by the southeast warm wet airflow on the southwest side of the high, and WNWC is controlled by the dry and cold northwest airflow on the south side of the low. Therefore, there is more precipitation in ENWC, and less in WNWC. According to the definition of the MI and WI, it can be seen from the figure that in the WA-EH type, the WI is lower and the MI is higher.

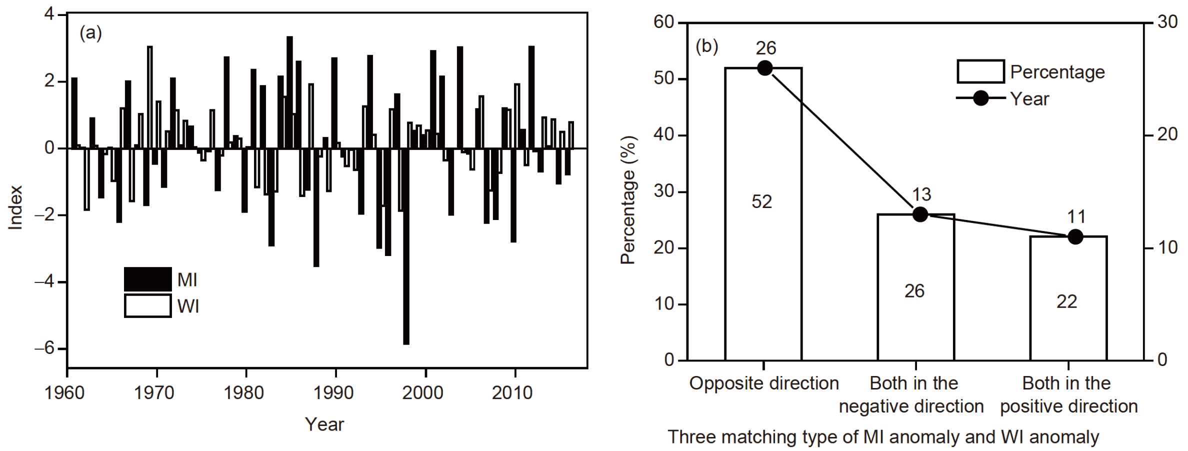

Figure 7 Variation of MI and WI (a) and its direction (b) of change in ENWC and WNWC during the flood season in 1961 to 2016.

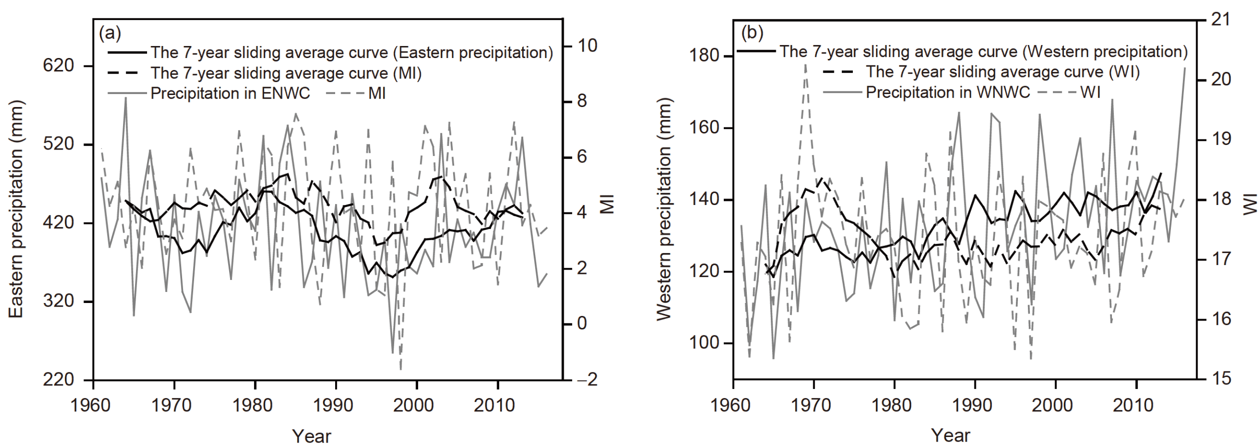

Figure 8 Comparison of EASM index and precipitation variation in ENWC (a) and the comparison of WI and precipitation variation in WNWC (b).

In the WH-EA type, conversely, the "low-high-low" wave train is formed in the middle and high latitudes. The pressure is low in the east and high in the west of China. The Xinjiang ridge of high pressure becomes weaker, and the East Asian trough becomes shallower (Zhong and Li, 2008). ENWC is mainly controlled by straight or northerly flow, while WNWC is mainly controlled by the easterly flow from the south side of the high. So there will be more precipitation in WNWC and less in ENWC. It can also be concluded from the figure that the WI is higher and MI is lower in the WH-EA type. Therefore, the precipitation seesaw variation in ENWC and WNWC and its correlation with the inverse variations of MI and WI can be basically explained (Zhang et al., 2004) by the adjustment and transformation of the geo-potential height field.

The comparison of 500 hPa wind fields between the WA-EH type and the WH-EA type in flood seasons (Figure 10) can further explain the circulation mechanism of seesaw variation in ENWC and WNWC. In the WA-EH type, ENWC is obviously controlled by warm and wet airflow from south to north, while WNWC is mainly controlled by dry and cold airflow from north or west to south. Therefore, ENWC is prone to rainfall, while WNWC is not. In the WH-EA type, ENWC is mainly controlled by the north dry and cold airflow, while WNWC is obviously controlled by the warm and wet airflow from the southwest. Therefore, ENWC is not prone to rainfall, while WNWC is.

A further analysis of the vertical velocity field difference between the WA-EH type and the WH-EA type at 500 hPa (Figure 11) shows that the vertical velocity difference in ENWC is basically positive while it is negative in WNWC. It indicates that compared with the WH-EA type, in the WA-EH type, there is a stronger upward tendency of the airflow in ENWC and a stronger subsidence tendency in WNWC. Therefore, compared with the WH-EA type, in the WA-EH type, the condition is more favorable for the precipitation in ENWC, and is bad for precipitation in WNWC. Thus, both the characteristics of the wind field and the vertical velocity field can support the aforementioned analytical conclusions from the potential height field.

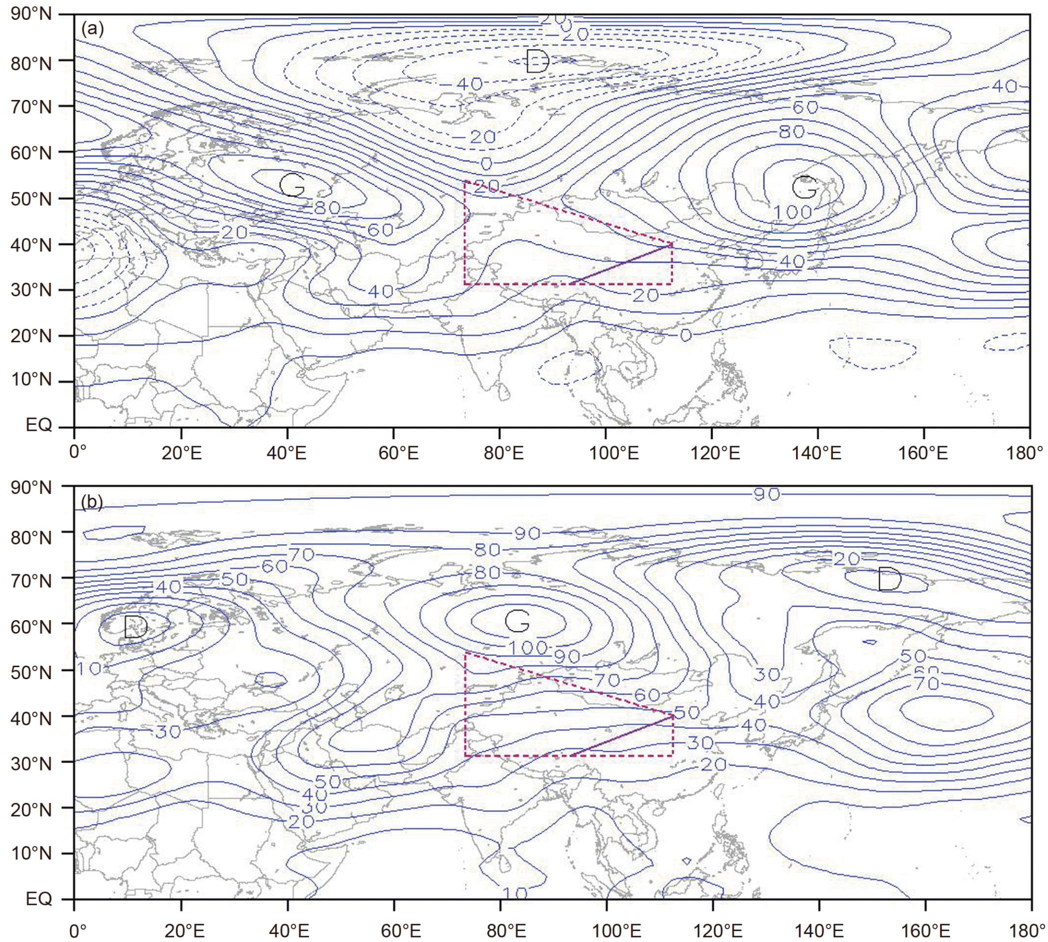

Figure 9 Comparison of 500-hPa geopotential height anomaly field during the flood season between WA-EH style (a) and WH-EA style (b) (unit: gpm). The dotted red line represents the northwest region, and the solid purple line divides it into the west (left quadrilateral region) and the east (right triangle region), the same as below.

The opposite variation of precipitation in Northwest China is influenced by various circulation situations, but the influence of the monsoon and westerly circulation cannot be ignored. When the high ridge of western Pacific subtropical anomaly changes to the south in summer, the EASM circulation becomes weak, the drought degree in the arid region of East Asia has a tendency to extenuate or become wet, and the geopotential height anomaly appears to be low in ENWC and high in WNWC. The cold air in high latitude reaches the middle latitudes, which brings more precipitation in ENWC and less precipitation in WNWC. On the contrary, the arid trend of the semi-arid area on the edge of the EASM is increasing, and the precipitation in WNWC is more than that in ENWC (Zhang and Tao, 2003; Zhu et al., 2012; Zuo et al., 2012; Liu et al., 2018). The meridional migration of the westerly jet is also an important factor influencing the reverse change of precipitation in NWC. When the subtropical jet in West Asia is strengthened to the south, there is more precipitation in WNWC to the west of 100°E. When the East Asia jet and West Asia jet flows are significantly northward and strengthened, the summer precipitation in ENWC to the east of 100°E is relatively high, which is estimated to be related to the secondary circulation stimulated by the jet current (Wang et al., 2012).

However, the inverse but interrelated correlations between the variation of the EASM and the westerly circulation and the precipitation variation in ENWC and WNWC in flood seasons mean that, there is an interaction between them, or they may be manipulated by the same circulation factor to some extent. Theoretically, the summer monsoon belongs to the subtropical weather system, and the westerly circulation is also related to the movement system of the airflow from the subtropical high to the subpolar low, which is formed by the geostrophic force. Thus they have the same origin actually. At the same time, the variation of the EASM will also influence the westerly zone fluctuation through the circulation structure adjustment, and then affect the water vapor transport from the westerly zone to NWC. Therefore, there is an interaction mechanism between them, and they are affected by the control mechanism caused by the same circulation factors.

In fact, the EASM circulation usually interacts with the

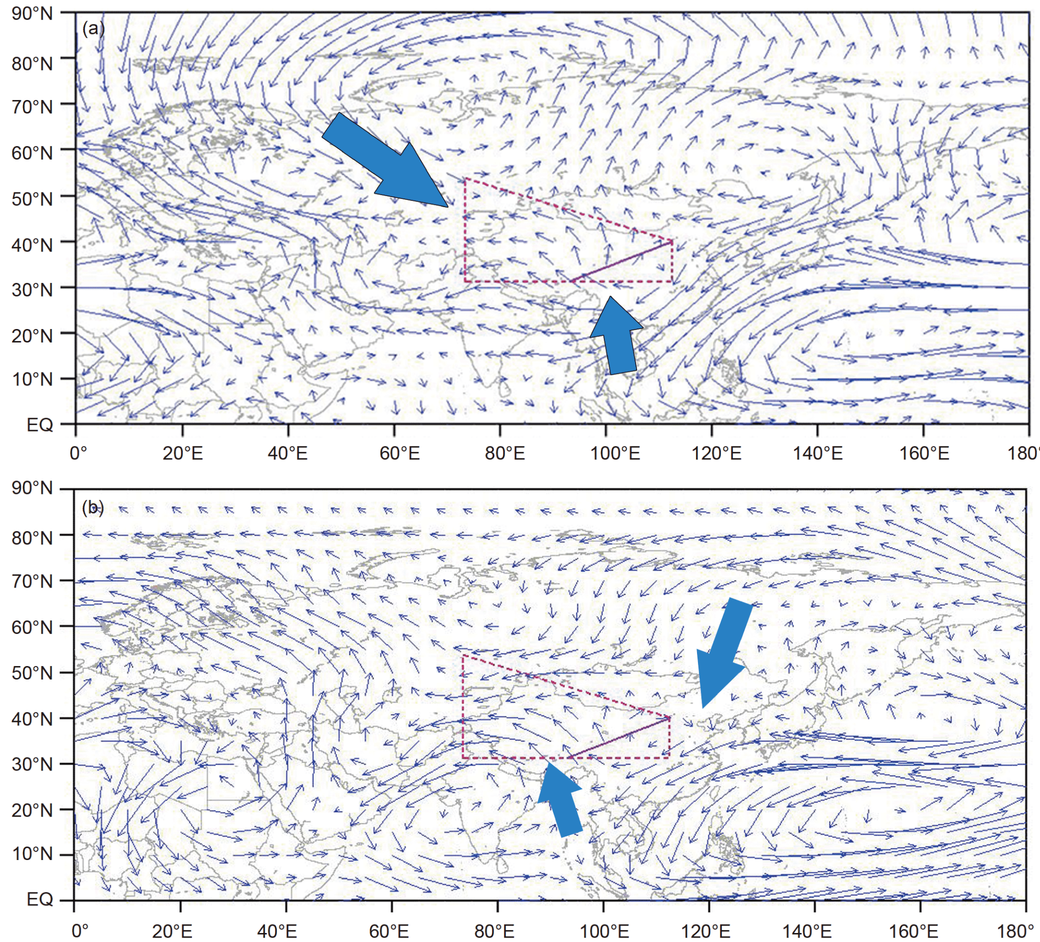

Figure 10 The correlation of 200-hPa UV wind anomaly field during the flood season between WA-EH style (a) and WH-EA style (b) (unit: m s^{-1})

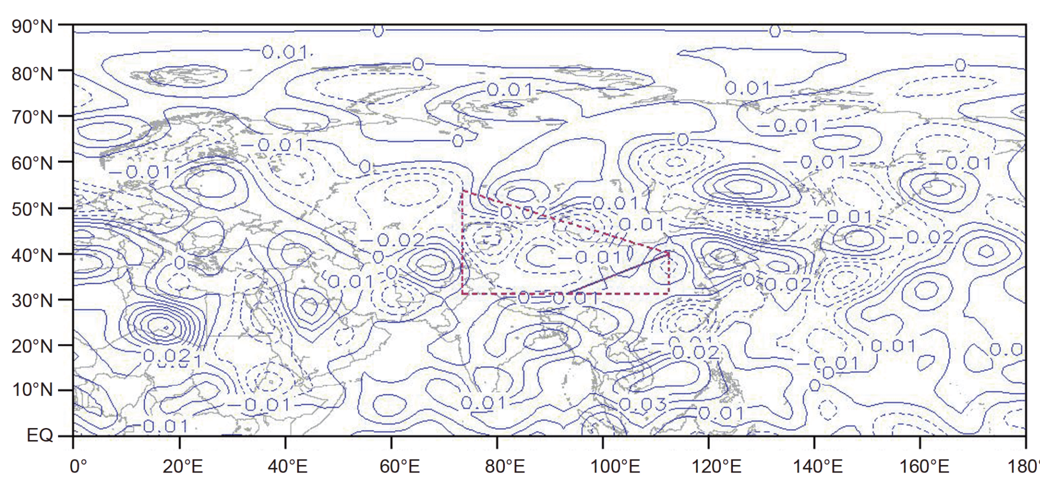

Figure 11 The difference of 500-hPa vertical velocity field between WA-EH style and WH-EA style (unit: Pa s^{-1}).

westerly circulation through the subtropical high. The latent heat released by summer monsoon convections results in the circulation distribution of lower level cyclone and upper level anticyclone, which will lead to the formation of downdraft over the Indian Peninsula west of the heating area and strengthen the low level anticyclone. It does not contribute to the southward inclination of the lower subtropical ridge and the development of the westerly circulation (Liu, 2013). Therefore, if the EASM is stronger, the westerly wind will be weaker, thus the precipitation in ENWC and WNWC will increase and decrease, respectively.

The South Asia High is undoubtedly the most likely factor that can manipulate the EASM and the westerly zone. As a powerful circulation system in the northern hemisphere, the summer South Asia High can cover a wide range of areas, including the northern Arabian Peninsula, the Iranian Plateau, the Qinghai-Tibet Plateau, the eastern China and the Western Pacific Ocean. The mid-latitude westerlies and the EASM and their interactions are often adjusted by changes of the South Asia High (Zhou, 2014). In addition, the South Asia High has a significant effect on the deepening and weakening of the trough and ridge in the middle and high latitudes of the northern hemisphere. Besides, its east-west oscillation is related to the long wave adjustment of the westerly zone. Past studies have shown (Tao and Zhu, 1964; Tan et al., 2005) that the 100 hPa South Asia High and the western Pacific subtropical high at 500 hPa always head for opposite zonal directions. If the ridge line of the South Asia High moves northeastward, the ridge line of the subtropical high will move northwestward. Thus the monsoon will intensify, and the north margin of the monsoon will go northwestward. Moreover, it will block the eastward development of the westerly wind, resulting in the weakening of the westerly circulation. As a result, the precipitation will increase in ENWC and decrease in WNWC, thus the WA-EH type will be formed. If the ridge line of the South Asia High moves southwestward, the area from Xinjiang to Central Siberia will be a ridge of high pressure. Then the western Pacific subtropical high will weaken and move to the southeast, and it is conducive to the eastward development of westerly circulation and the increasing of WI. As a result, there will be less precipitation in ENWC and more precipitation in WNWC (Zhang et al., 1997; Wei et al., 2012; Wang et al., 2017), which is the WH-EA type. Since the 21st century, the change of South Asian monsoon have caused the westerly jet in mid-latitude area of China to shift to the southeast, and the anomalous circulation caused the precipitation to increase in the arid region of Central Asia, that is, the precipitation increase in WNWC (Zhang, 1999; Wei et al., 2012; Zhao et al., 2014; Wei et al., 2017).

Figure 12 presents the comparison of the geopotential height fields at 100 hPa between the WA-EH type and the WH-EA type during the flood season. The distribution and intensity of the South Asia High in the two matching types of precipitation seesaw variations in ENWC and WNWC are obviously different. In the WA-EH type, the center of the South Asia High is more northeastward and can reach 32°33′N and 88°34′E. While in the WH-EA type, the center of the South Asia High can only reach 31°58′N and 58°39′E, which is more southwestward. The center of the South Asia High in WA-EH reaches further. It proves that the adjustment of the South Asia High plays an important role in maintaining and transforming the two matching types of precipitation seesaw variations in ENWC and WNWC during the flood season.

Of course, the adjustment of the South Asia High is affected by many factors. However, as the most important global sea surface temperature forcing event, the ENSO, which can affect the South Asia High, is undoubtedly very important. ENSO events can control the time and strength of summer monsoon onset by influencing the distribution of the upper South Asia High, the characteristics of middle subtropical anticyclones and the inertial instability intensity of the lower layer. Under the combined influence of high, middle and low laminar flow fields related to ENSO, the rising motion of the Arabian Sea is weak, which is not conducive to the establishment of summer monsoon convection, and the onset of summer monsoon will be late. The effect of La Niña event is opposite to that of ENSO. Some studies have proved that the South Asia High is weak in the year of ENSO, and there is less precipitation in ENWC and more precipitation in WNWC (Zhang et al., 2003). The trend comparison between the precipitation and the intensity in ENWC (Figure 13a) and WNWC (Figure 13b) also shows that the ENSO intensity (China Standard Press, 2017) is inversely related to the precipitation in ENWC, while it is in phase to the precipitation in WNWC.

In addition, the Qinghai-Tibet Plateau is known as the third pole of the world, and is the highest place with the most complex terrain on the earth. Its influence of the heating field on the advance and retreat of the South Asia High is obvious. When the underlying surface of the Qinghai-Tibet Plateau increases in a considerable area of sensible heat, it is also beneficial to the precipitation in the southeast of NWC (Li et al., 1997). The plateau monsoon affects the EASM and South Asia summer monsoon through the easterly air flow, thus affecting the precipitation in NWC. When the plateau monsoon becomes strong, it is favorable for water vapor to be transported to the WNWC, so there will be more precipitation. On the contrary, when the Qinghai-Tibet Plateau summer monsoon is interrupted and controlled by the high pressure system, the anomalous northeasterly airflow lies on the east side and the South Asia summer monsoon is weakened, which hinders the northward transport of water vapor from the Bay of Bengal, and the precipitation in WNWC (Qi et al., 2015). If the temperature of the plateau is higher, it will cause the South Asia High to move northward, and the westerly circulation will stay longer in the middle latitude. On the contrary, if the temperature of the plateau is lower, it will cause the South Asia High to move southward, and the westerly circulation will stay in the middle latitude for a shorter time (Fang et al., 2016). On the inter-decadal scale, the contribution of Pacific Decadal Oscillation (PDO) is worthy of much attention. In general, the conversion of the positive and negative phases of PDO will change the intensity of the subtropical westerly jet in the upper troposphere, thus resulting in the adjustment of the intensity of the South Asia High and the tropical easterly jet in the southern part of the troposphere. The anomalous signals are trans-

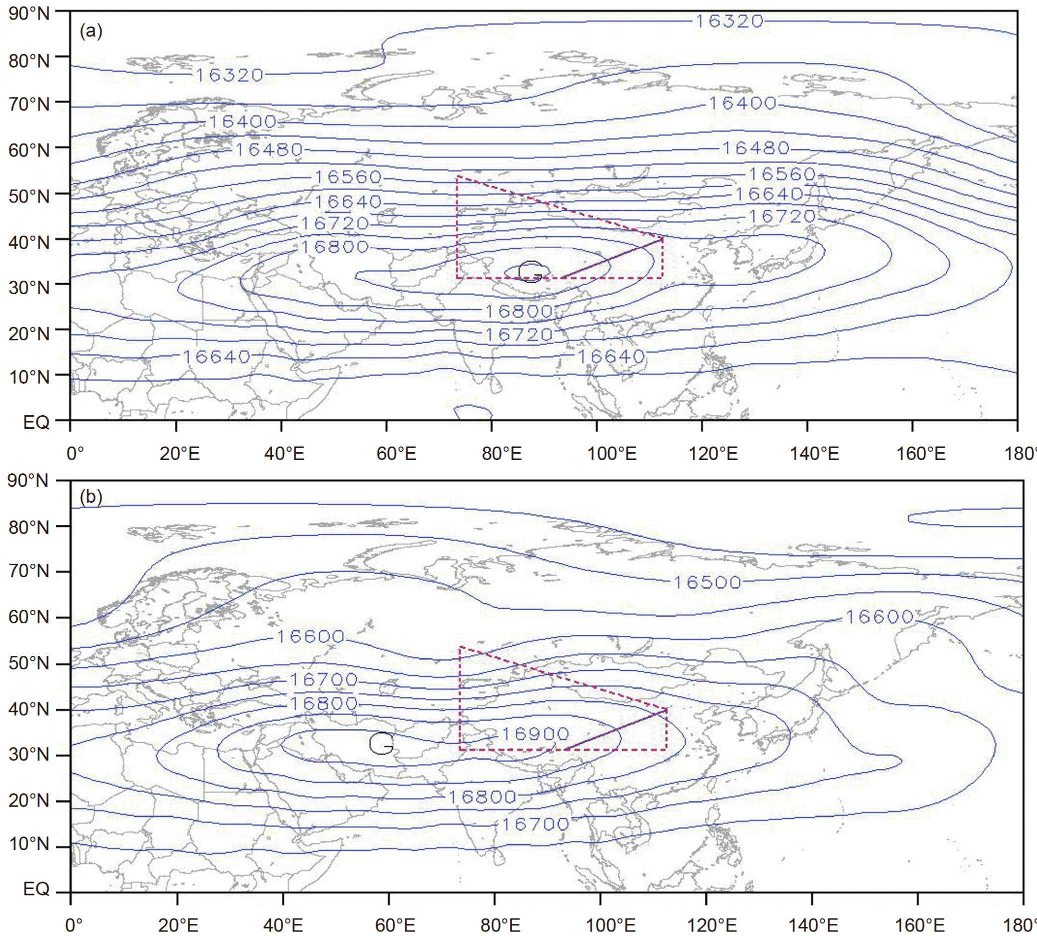

Figure 12 Compression of 100-hPa geopotential height field between WA-EH style (a) and WH-EA style (b) in typical years during the flood season (unit: Pa s^{-1})

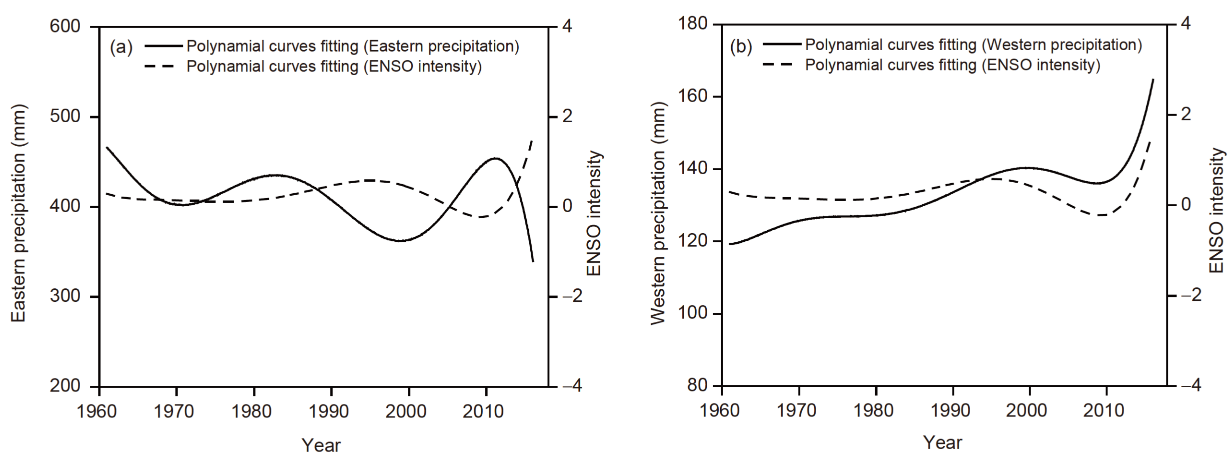

Figure 13 Comparison of the variation trend between ENSO intensity and the annual precipitation in (a) eastern and (b) western Northwest region.

mitted to the lower troposphere through the zonal vertical circulation over the tropical Indian Ocean, thus changing the EASM circulation and the westerly circulation (Shi et al., 2017). That is why the EASM and the westerly circulation show significant inter-annual and inter-decadal quasi-periodic variations similar to ENSO and the surface heating field of the plateau (Xu et al., 1990; Li et al., 2015).

7. Conclusion and discussion

The precipitation variation trend in flood seasons in NWC varies in different parts, especially in ENWC and WNWC. The precipitation in ENWC and WNWC during the flood season shows significant seesaw variations, on the inter-annual scale, on the inter-decadal scale and in their general trends.

Moreover, the precipitation seesaw variation in ENWC and WNWC is mainly related to the influence of different circulation systems in these two parts. The precipitation in ENWC is mainly controlled by the summer monsoon system, while the precipitation in WNWC is mainly controlled by the westerly zone system. It is because of the inter-annual, decadal and multiyear reverse phase variations between MI and WI that the seesaw variation in ENWC and WNWC during the flood season is formed.

At the same time, in the transformation between two precipitation trend matching types (the WA-EH type and the WH-EA type), the influence of different grades of precipitation in ENWC and WNWC is not the same. The seesaw variation of the general trend is mainly related to the contribution of middle grade precipitation (15 to 80 mm). But the seesaw variation on the inter-decadal scale is mainly related to the contribution of lesser grade precipitation (below 60–70 mm). Changes in other grades of precipitation may be counterproductive.

Besides, in two precipitation trend matching types, the middle and high latitudes in the WA-EH type preserve "high-low-high" wave trains, and the circulation form is "low in the west, high in the east" in NWC. The middle and high latitudes in the WH-EA type preserve the opposite "low-high-low" wave trains, and the circulation form is "high in the west, low in the east" in NWC. The two wave train patterns cause not only the completely different precipitation variations in ENWC and WNWC, but also the two inverse matching forms of MI and WI.

The formation of the inverse relationship between MI and WI is related to the interaction between the EASM and the westerly circulation through the subtropical high. It is also related to the oppositing effect of the South Asia High on the EASM and the westerly circulation. Although the factors affecting the South Asia High are quite complex, the ENSO and plateau heating fields are most worthy of attention, for their inter-annual and inter-decadal quasi-periodic oscillations may be the main causes for the inter-annual and inter-decadal variations of the South Asia High. It also leads to a high probability of the precipitation seesaw phenomenon in ENWC and WNWC during the flood season.

The precipitation in ENWC and WNWC does not always present as seesaw variation. So do the westerly circulation and the EASM. Sometimes their variations are consistent. The reason may be that the circulation factors affecting precipitation in flood seasons in NWC are not limited to the EASM and the westerly circulation, and sometimes the influence of such factors as the northeast cold vortex region and the Mongolian high are also important. Moreover, their influence on precipitation, summer monsoon circulation and westerly circulation in NWC is also complicated (Xun, 2012). This problem has yet to be analyzed from different angles in future researches and it even requires numerical simulation experiments of several schemes to fully understand the roles played by various atmospheric circulation systems.

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