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Droughts near the northern fringe of the East Asian summer monsoon in China during 1470–2003

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Abstract Historical annual dry–wet index for 1470–2003 combined with instrumental precipitation since 1951 were used to identify extremely dry years and events near the northern fringe of the East Asian summer monsoon in China—the Great Bend of the Yellow River (GBYR) region. In total, 49 drought years, of which 26 were severe, were identified. Composites of the dry–wet index under the drought years show an opposite wet pattern over the Southeast China. The longest drought event lasted for 6 years (1528–1533), the second longest one 4 years (1637–1640). The most severe 2-year-long drought occurred in 1928–1929, and the two driest single years were 1900 and 1965. These persistent and extreme drought events caused severe famines and huge losses of human lives. Wavelet transform applied to the dry–wet index indicates that the severe drought years are nested in several significant dry–wet variations across multiple timescales, i.e., the 65–85 year timescale during 1600–

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1800, 40–55 year timescale before 1640 and 20–35 year timescale mainly from 1550 to 1640. These timescales of dry–wet variations are discussed in relation to those forcing such as cycles of solar radiation, oscillation in the thermohaline circulation and the Pacific Decadal Oscillation (PDO). Comparing 850 hPa winds in Asia in extremely dry and wet years, it was concluded that dry–wet variability in the GBYR region strongly depends upon whether the southerly monsoon flow can reach northern China.

1 Introduction

Monsoon climate is widely distributed around the world. It covers about one fourth of the continents and influences nearly half of the world's population. The Asian monsoon includes three subsystems, i.e., the Indian (South Asian) monsoon, the East Asian monsoon and the Northwest Pacific monsoon (Wang and Lin 2002). The East Asian monsoon is located in the subtropics along a band from the Yangtze River in China to Japan and is separated from the tropical monsoon (Ding 2004).

The unique topography of China, particularly the Tibetan Plateau, has a strong influence on the intensity and location of the East Asian monsoon. Every summer, the westerly flow to the north of the Tibetan Plateau and the southerly monsoon flow over the eastern China converge in the lee side, forming a subtropical front that gradually moves from South China to the Yangtze River basin and reaches northern China in late July (Hu and Qian 2007). The intraseasonal march of the monsoon can lead to severe floods or droughts in different regions and produce interdecadal-scale anomalous climate events such as the severe drought in Northwest China (Qian et al. 2007).

In the last two decades, several East Asian monsoon indices have been established (e.g. Huang and Yan 1999; Guo et al. 2003; Zhang et al. 2003; Zhao et al. 2007). While these indices are closely linked with the summer precipitation variability along the Yangtze River basin, they cannot indicate the dry–wet variation in northern China (Hu and Qian 2007).

By using the dry–wet indices over 100 sites in eastern China (Central Meteorological Bureau 1981) since 1470 and instrumental summer precipitation in eastern China since 1951, Shen et al. (2007) investigated three exceptional drought events that occurred in 1586–1589, 1638–1641, and 1965–1966 in the North China. They found that all these droughts developed firstly in North China and then either expanded southward or moved to the Yangtze River basin. Qian et al. (2007) found a similar drought event in the Great Bend of the Yellow River (GBYR) region during 1927–1929. These two studies only focused on the four short spells over the last 500 years by using the same dry–wet indices. For sustainable economical and life-supporting developments in the GBYR region in northern China, it is necessary to study drought events in a longer historical perspective. How many drought events occurred in the region during the last five centuries? What are the possible causes for their formations? This study tries to answer these questions.

The paper is organized as follows. Data and analysis methods are described in Section 2. The northern fringe of the summer monsoon is identified in Section 3. Drought events that occurred during the last 534 years in the region are extracted in Section 4. The temporal evolution of the regional dry–wet alternation and possible causality are discussed in Section 5. What circulation causes the dry–wet pattern is explored in Section 6. Finally, a summary and conclusion are provided in Section 7.

2 Data and analysis method

Three datasets were used in the analysis. The first dataset is the daily precipitation data from 726 stations for the period 1951–2003 obtained from the Chinese National Meteorological Center. This dataset was used by Qian and Qin (2008) and has gone through quality control (Feng et al. 2004). It compares favorably with other datasets and model simulation (Qian and Leung 2007). In this paper, data from 486 of the 726 stations were used to identify the precipitation characteristics. The second dataset is the NCEP/NCAR reanalysis data (Kistler et al. 2001). The 850 hPa winds from the reanalysis data were used to explain the dry–wet patterns in eastern China. The third dataset is the summer (May–September) dry–wet index series from 100 sites in eastern China from 1470 to 2003, which was extracted from over 2,000 historical documentary records, including the government weather book “Clear and rain records”, local government drought/flood reports and private diaries. The index was categorized into five grades, namely extremely wet (grade 1), wet (grade 2), normal (grade 3), dry (grade 4), and extremely dry (grade 5). Since 1951 onwards, the dry–wet indices for this period are constructed based on the instrumental observations. The same data have been used in some previous studies (Song 2000; Hu and Feng 2001; Shen et al. 2007) and published as yearly charts of dryness/wetness in China for the last 500 years (Central Meteorological Bureau 1981).

Wavelet transform using the “Morlet” function (Torrence and Compo 1998) is applied to detect the interdecadal variations from the above-mentioned long-term series. If a close pair of minimum and maximum centers for wavelet coefficients appear at a certain timescale, we consider that there is a quasi periodicity at that timescale.

3 The northern fringe of the summer monsoon

There were different definitions of the northern fringe of the East Asian summer monsoon based on air temperature, moisture, monsoon precipitation and lower-tropospheric southwesterly winds. In 1940s, Tu and Huang (1944) constructed a combined variable to identify the advance and retreat of the East Asian summer monsoon in eastern China. They define the northern fringe of the summer monsoon as the place where the warm-humid air mass meets with the cold–dry air mass in northern China. Synthesized indices to determine the northern fringe of the summer monsoon in China were proposed by Gao (1962). He identified the climatological mean location of the northern fringe in 40° N, gradually extending northward to 50° N at 120° E. The interannual and interdecadal changes of the fringe form a migration zone of summer monsoon activities, where the natural ecosystem is sensitive and vulnerable (Fu 2003).

It was well established that the seasonal advance of the summer monsoon in eastern China behaves in a stepwise way from the middle of May, accompanied by the northward moving of the northwest Pacific subtropical high (Lau and Yang

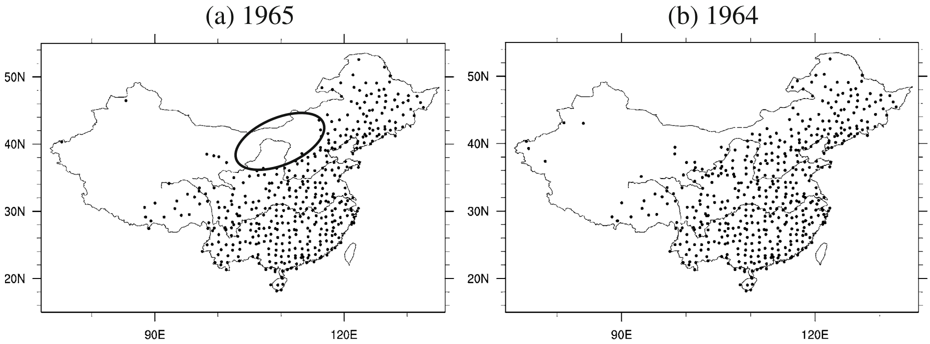


Fig. 1 Stations that were experienced 7 mm/day precipitation in the years of **a** 1965 and **b** 1964. Each *dot* represents one station. The *oval* in **a** indicates the dry GBYR region

1997; Wang and Lin 2002; Qian et al. 2007). To define the rainy season, several criteria of precipitation intensity were developed, including 4, 5, 6, and 7 mm/day amount. Depending on the strength of the monsoon, the northernmost locations of various precipitation intensities vary from year to year, leading to large interannual dry–wet variations in the GBYR region. As an example, the average precipitations from May to September over the GBYR region in 1964 and 1965 are 78.4 mm and 26.0 mm, respectively. The 7 mm/day precipitation isoline reached the GBYR region in 1964 but not in 1965 (Fig. 1). As a matter of fact, in northwestern China, 7 mm/day precipitation can be experienced only at a few stations, while in southeastern China the 7 mm/day precipitation arrives every year. Therefore, the GBYR region is a transitional zone that separates the non-monsoon area to its northwest and the monsoon area to its southeast. It is thus considered the northern fringe of East Asian summer monsoon.

4 Drought events

Based on the yearly dry domain (Fig. 1) and decadal dry area (Qian et al. 2007), ten sites are chosen from the GBYR region in Fig. 2 to represent the study area. Dry–wet indices in these ten sites were averaged to examine drought events in the defined region.

Table 1 lists the 49 years with the regional dry–wet grade above 4.0, of which 26 years are above 4.5. Drought years with the grade above 4.0 were concentrated in the late fifteenth to seventeenth century and the twentieth century. Nine years of severe drought events with the grade above 4.5 are observed from 1500 to 1599, five during 1900–1999 but only one severe drought appeared in the eighteenth century (1759). Due to the drought events in the GBYR region, no-flow events have been frequently observed in the lower reaches of the Yellow River since the 1970s (Qian and Zhu 2001).

Two composite distributions of dry–wet indices by the 49 drought years and 26 severe drought years are shown in Fig. 2. Obviously, the drought center with the grade above 4 is located in the GBYR region. By contrast, a large wet area with grade below 2 is found in the Southeast China.

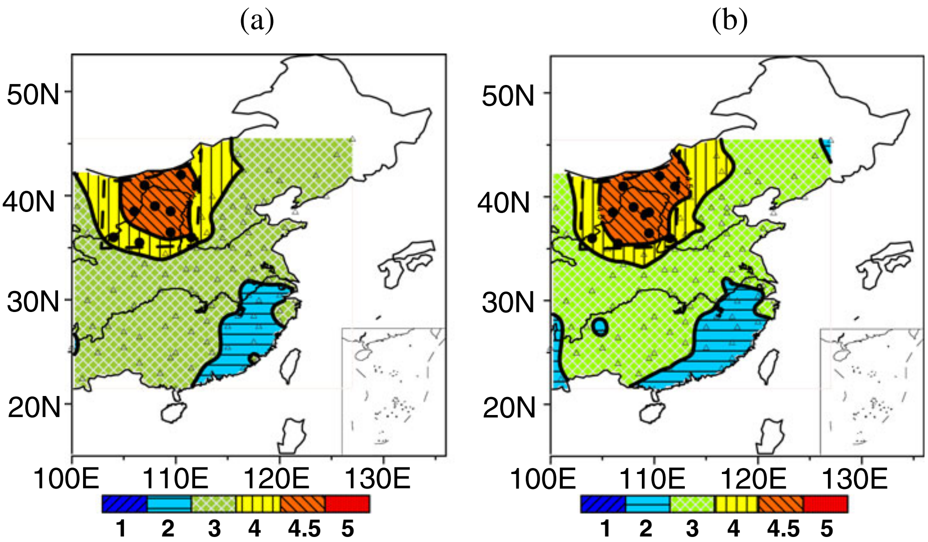


Fig. 2 Composite distributions of dry–wet index with **a** the regional average dry grades above 4 for the 49 years and **b** the regional average dry grade above 4.5 for the 26 years as listed in Table 1. *Triangles* indicate 90 sites over eastern China, in addition to the ten sites marked by the *dots* in the GBYR region. The dry–wet grades vary from 1 (extremely wet) to 5 (extremely dry)

5 Regional dry–wet evolutions

The regionally averaged annual series of the dry–wet index for the GBYR region from 1470 to 2003 is given in Fig. 3. The number of years with grades above 3.0 is more than that of years below 3.0, which means droughts occurred frequently in the

Table 1 Drought years in the GBYR region with the dry–wet grades above 4.0 in different centuries

Century	1470~1499	1500~1599	1600~1699	1700~1799	1800~1899	1900~1999
Year (grade)	1473 (4.2)	1500 (4.1)	1609 (4.7)	1711 (4.2)	1824 (4.2)	1900 (5.0)
	1481 (4.3)	1516 (4.3)	1610 (4.1)	1714 (4.1)	1833 (4.1)	1928 (4.9)
	1483 (4.3)	1521 (4.5)	1629 (4.8)	1720 (4.4)	1846 (4.7)	1929 (4.8)
	1484 (4.9)	1528 (4.8)	1630 (4.5)	1721 (4.4)	1877 (4.9)	1957 (4.3)
	1489 (4.1)	1529 (4.6)	1637 (4.5)	1747 (4.2)	1878 (4.5)	1965 (5.0)
	1495 (4.5)	1531 (4.6)	1638 (4.4)	1759 (4.5)	1892 (4.8)	1972 (4.8)
		1532 (4.8)	1639 (4.4)		1899 (4.2)	1980 (4.2)
		1533 (4.8)	1640 (4.8)			1986 (4.2)
		1568 (4.5)	1697 (4.1)			1991 (4.3)
		1582 (4.5)				1997 (4.1)
		1586 (4.8)				
No. (S > 4.0)	6	11	9	6	7	10
No. (S > 4.5)	2	9	5	1	4	5

Shaded years have been analyzed by Shen et al. (2007) and Qian et al. (2007). The last two rows are the numbers (no.) of year with the grade >4.0 and >4.5

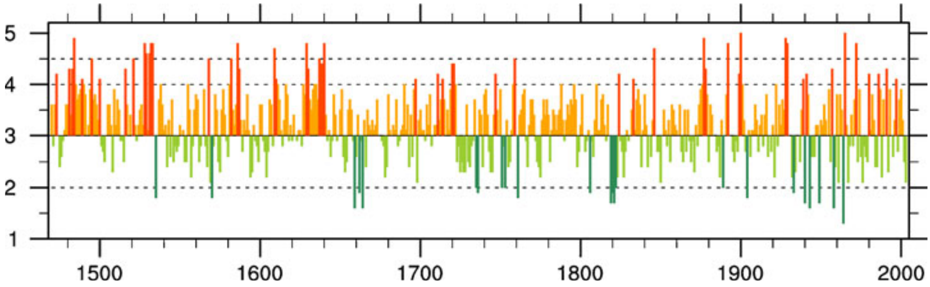


Fig. 3 Annual series of dry–wet index from 1470 to 2003 averaged over the GBYR region. *Orange and green bars* indicate that the dry–wet indices are above 3 grades and below 3 grades, respectively. Drought and wet years listed in Tables 1 and 2 are highlighted with *darker colors*. *Three dashed reference lines* are 4.5, 4.0 and 2.0, respectively

region. Two most severe drought events occurred in 1900 and 1965 with the regional average grade of 5.0 and seven 2-year-long drought events occurred in 1483–1484, 1609–1610, 1629–1630, 1720–1721, 1877–1878, 1899–1900, and 1928–1929 (Table 1). The longest drought period in the GBYR region was from 1528 to 1533 with an interruption in 1530. Another long drought period was noted from 1637 to 1640 for 4 years. Three exceptional drought events investigated by Shen et al. (2007) were centered in 1586, 1640, and 1965 with the dry grade above 4.8. A severe drought in the late 1920s in northern China coincided with the anomalous warm and dry decade (Qian et al. 2007). The sustained drought and plague of locusts caused repeated crop failures, leading to a severe famine from 1927 to 1929 in the northern China. Thirty-four million people suffered from the severe drought, and at least ten million died (Deng 1937).

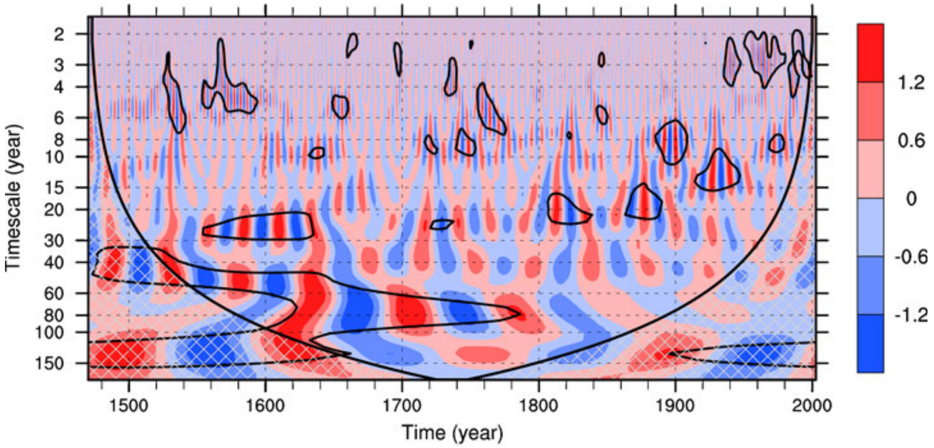
There were totally 23 wet years with the grade below or equal to 2 (Table 2). During the seventeenth century, a wet spell was present from 1659 to 1664. Two-year-long wet events appeared in 1735–1736 and a long-lasting wet event occurred from 1819 to 1822 for 4 years. During the twentieth century, wet years were frequently observed from 1930s to the early 1960s.

The real-part coefficients of the wavelet transform (Fig. 4a) indicate that there are significant signal bands across multiple timescales for different periods. For example, there are significant variations at timescales of 65–85 years during 1600–1800, 40–45 years before 1640 and 20–30 years mainly during 1550–1640. The bands

Table 2 Same as in Table 1 except the dry–wet grade ≤2.0 in different centuries

Century	1470~1499	1500~1599	1600~1699	1700~1799	1800~1899	1900~1999
Year (grade)		1535 (1.8) 1570 (1.8)	1659 (1.6) 1662 (1.9) 1664 (1.6)	1735 (2.0) 1736 (1.9) 1751 (2.0) 1753 (2.0) 1761 (1.8)	1806 (1.9) 1819 (1.7) 1820 (1.9) 1821 (1.7) 1822 (2.0) 1889 (2.0)	1904 (1.8) 1933 (1.9) 1940 (1.7) 1943 (1.6) 1949 (1.7) 1958 (1.6) 1964 (1.3)
No. (S ≤ 2.0)	0	2	3	5	6	7

(a) Wavelet Real-part Coefficient



(b) Wavelet Bands

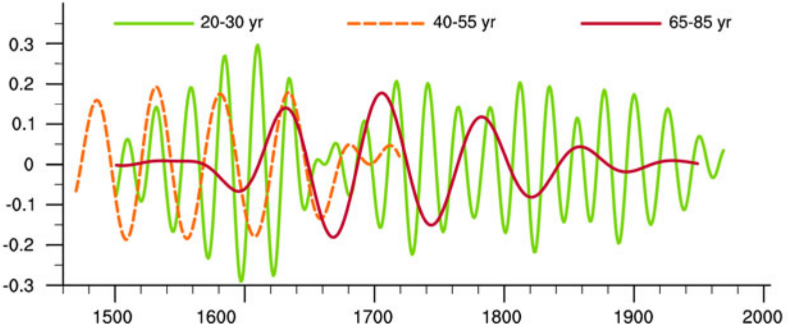


Fig. 4 Analyses of the annual dry–wet series over the GBYR region from **a** the real-part coefficients of the wavelet transform. The *thick contour* encloses regions of greater than 90% confidence of wavelet power for a red-noise process with a log-1 coefficient of 0.26. *Cross-hatched regions* indicate the "cone of influence". **b** Three bands of coefficient components with timescales of 20–30, 40–50 and 65–85 years

of coefficient components changes from one time period to another as Fig. 4b shows. In addition, quasi-10-year timescale is also observed in several periods.

The quasi-10 year and 20–30 year timescales are close to that of the solar activity (e.g. Mitra et al. 1991; Currie and O'Brien 1992; Linderholm 2001). Recently, Qian and Lu (2010) found solar radiation cycles at the 22-year timescale from 1850 to 2000, which may be linked with the 20–30 year band in Fig. 4b. The quasi-10 year timescale of dry–wet variation may be also linked with the solar radiation at the same timescale. The 40–45 year timescale may be connected with the 40–50 year irregular oscillation in the thermohaline circulation in the North Atlantic (Greatbatch and Zhang 1995). And 65–85 year timescale appears to correspond to the 60–80 year oscillation in the atmosphere-ocean system (e.g. Schlesinger and Ramankutty 1994). During the twentieth century, there were two negative spells of Pacific Decadal Oscillation (PDO) in 1910s and 1950s–1970s and two positive spells in 1930s and 1980s. Shen et al. (2006) analyzed the relationship between the PDO index and summer dry–wet condition in eastern China. Then, they reconstructed PDO records since 1470 A.D. using proxy data of summer precipitation over eastern China. A 62 year timescale predominates in the PDO series (Qian and Lu 2010), which is possibly linked with the obvious 65–85 year dry–wet cycle in the GBYR region from 1600 to 1800 (Fig. 4b).

6 Explanation of dry–wet patterns

For the GBYR region, the atmospheric circulation, which brings moisture from seas located in the lower latitudes, play a crucial role for the dry–wet conditions. Thus, an analysis on the circulation over the region would be helpful. Unfortunately, there are only data on the circulation over the last 50 years for Asia. Thus, the analysis cannot be made over the period when reanalysis data are not available. Nevertheless, the understanding of the recently climate variability may provide useful analogues for the past climate patterns (e.g. Antonsson et al. 2008).

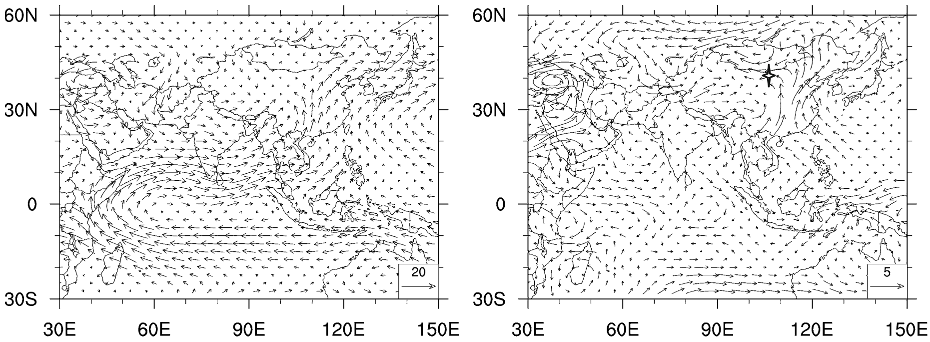
For the period from 1951 to 2003, there is no significant trend of the observed precipitation in the GBYR region. Dry and wet years are selected by the summer (May–September) mean precipitation. Table 3 lists the seven dry years with the summer precipitation less than 44.5 mm and two wet years with the precipitation more than 78.0 mm. The year of 1965 was extremely dry with the summer precipitation of 26.8 mm. During the first three decades, there was only one dry year in a decade but the frequency doubled in the 1980s and 1990s. Wet events were very few and only occurred in 1958 and 1964.

Based on results shown in Table 3 and the opposite dry–wet conditions in 1965 and 1964 (Fig. 1), a comparison analysis for the severe dry year 1965 and severe wet year 1964 were made and shown in Fig. 5 in terms of 850 hPa wind and its anomalous pattern. The southerly monsoon winds over eastern China were much stronger in 1964 than in 1965, bringing more moisture to the GBYR region and generating more precipitation along the Yellow River valley. Weak southerly winds would also slow down the march of the monsoon front, resulting in more precipitation in South China (Fig. 2). As for the strength of the southerly winds, it depends upon the heat contrast between the north Pacific and the Tibetan Plateau over Asia (Zhao et al. 2007). The anomalous patterns of wind show a cyclone (anti-cyclone) pattern in the GBYR region that further explains the extremely wet (dry) climate in the northern China.

Table 3 Dry and wet years of summer (May–September) precipitation (mm) derived from 1951 to 2003 over the GBYR region

Dry year <44.5 mm/summer		Wet year >78 mm/summer	
Year	Precipitation	Year	Precipitation
1957	41.8	1958	78.3
1965	26.8	1964	78.4
1972	40.8		
1980	44.2		
1986	42.0		
1991	39.5		
1997	42.5		

(a) 1964



(b) 1965

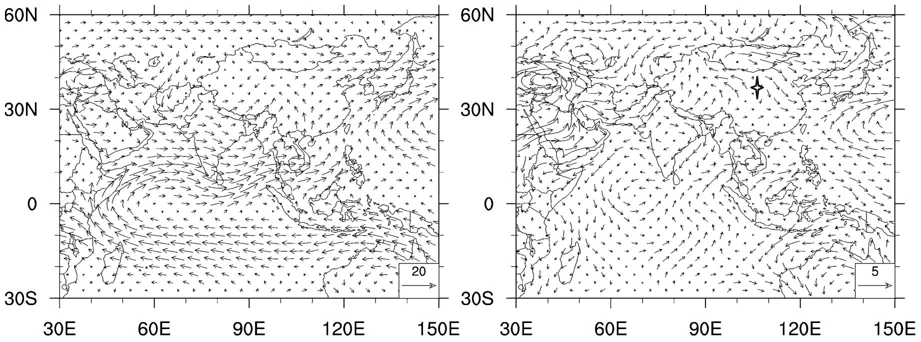


Fig. 5 **a**, **b** Comparisons of the summer (May–September) 850 hPa winds (*left panel*, m/s) and their anomalies (*right panel*, m/s) relative to the average between 1961 and 1990 at the years of 1964 (*up panel*) and 1965 (*below penal*). Sign "✦" indicates the location of the GBYR region

7 Summary and conclusions

Based on the seasonal northward advance of precipitation characterized by rain rate greater than 7 mm per day, the northern fringe of the East Asian summer monsoon is identified in the northern China. The northernmost location of the summer monsoon shifts from year to year and from decade to decade, which creates a highly variable and vulnerable transitional zone in terms of precipitation in the GBYR region. The extreme dry year 1965 and wet year 1964 exhibited significant difference in monsoon precipitation.

Using the yearly dry–wet series over the GBYR region, 49 drought years, of which 26 were severe, were identified in the past 534 years. There were seven 2-year long droughts in 1483–1484, 1609–1610, 1629–1630, 1720–1721, 1877–1878, 1899–1900 and 1928–1929, a 4 year drought from 1637 to 1640 and a 6 year drought from 1528 to 1533. Composites of dry–wet indices indicated that there is an opposite precipitation anomaly in the Southeast of China when the GBYR region is dry or extremely dry due to the circulation that favors precipitation in the south.

Several significant peak bands in the dry–wet variations on multiple timescales were derived from the wavelet analysis. These include the 20–30, 40–55 and 65–

85 year timescales for different periods, which are possibly associated with cycles of solar radiation, oscillations in the thermohaline circulation and PDO.

The instrumental observed precipitation combined with the reanalysis data were used to explain the difference of the circulation between dry and wet years. During the extremely dry summer of the GBYR region, which means there was weak southerly wind at 850 hPa in northern China. In the extremely wet summer, however, the strong southerly winds conveyed moisture straight to the northern China, resulting in above normal precipitation.

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