

Characteristics of anomalous precipitation events over eastern China during the past five centuries

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Abstract Characteristics of anomalous precipitation events during the past five centuries in North China (NC) and the middle-lower Yangtze River Valley (MLYRV) were investigated using the data network of dryness/wetness index (DWI) over eastern China. The high occurrence frequency of anomalous precipitation events mainly occurred at periods of high solar forcing, active volcanic eruption, and large anthropogenic forcing (the twentieth century). Coherence and dipole were the two dominant modes in spatial patterns of anomalous precipitation events. Coherent floods dominated the eighteenth and nineteenth centuries, whereas coherent droughts occurred frequently in the seventeenth and twentieth centuries. The dipole patterns of anomalous precipitation events were the most frequent in the twentieth century. NC experienced more floods in the cold periods than warm periods. Both NC and the MLYRV experienced far fewer droughts and more floods in the warm eighteenth century when natural climate forcing dominated, and more droughts in the twentieth century when anthropogenic forcing dominated. Coherent drought was the only spatial pattern of precipitation significantly associated with explosive low-latitude volcanic eruptions. The increased coherent droughts and

dipole patterns in the twentieth century support the findings of previous modeling studies that the tropospheric aerosols and human-induced land cover changes play important roles in the changes of summer rainfall over eastern China.

Keywords Anomalous precipitation events · Drought · Flood · Spatial pattern · Eastern China

1 Introduction

Anomalous precipitation events (i.e. droughts and floods) are the most frequent natural disasters in monsoonal Asia. They can cause great economic and societal losses in this most populated region of the world. Anomalous precipitation events thus have received increasing attention due to their significant impacts on economy, society, and environment (Easterling et al. 2000; Changnon et al. 2001; IPCC 2002).

In recent decades, eastern China has suffered increased droughts in its north and increased floods in its south (Sun et al. 1998; Xu 2001; Wu et al. 2006). The studies of climate models suggested that this trend could probably be attributed to the climate effects of black carbon aerosols (Xu 2001; Menon et al. 2002) and human-induced land cover changes (Fu 2002, 2003). This observed trend of moisture regime thus motivates us to investigate the temporal and spatial patterns of anomalous precipitation events over eastern China during the instrumental and historical times. This issue is important for understanding the climatological mechanisms of anomalous precipitation events and predicting droughts and floods in the future. Although the frequency of anomalous precipitation events and their spatial patterns have been extensively studied through observational data (e.g. Sun et al. 1998; Wang et al. 2000a,

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b; Qian et al. 2003a; Qian and Lin 2005; Zhai et al. 1999, 2005) and historical data (e.g. Wang and Zhao 1981; Zhang 1988; Zhang and Crowley 1989; Song 2000; Qian et al. 2003a and 2003b), this study is different on four lines of methodology and focus. First, we used a new approach to detect anomalous precipitation events. Second, we determined the dominant spatial patterns of anomalous precipitation events using the datasets consisting of identified anomalous precipitation events (i.e. discarding the “normal” years) instead of full data (including “normal” years) as used in the previous studies (e.g. Wang and Zhao 1981; Qian et al. 2003b). Third, we focused on the temporal variations of dominant spatial patterns of anomalous precipitation events, which have less been emphasized in previous studies. Additionally, the summer precipitation of eastern China is also affected by climate forcings such as solar and volcanic forcing (Zhang and Zhang 1994; Gong and Wang 2000a; Bradbury 2006), and land surface conditions such as surface air temperature and soil moisture in winter and spring (Guo 1985, 1994; Ding 1991; Robock et al. 2003; Wu and Chan 2005). So the relationships among climate forcings, land surface temperature, and anomalous precipitation events were discussed by a comparison of reconstructions of winter half-year (October–April) temperature (Ge et al. 2003) and climate forcings (Jones and Mann 2004) with our identified anomalous precipitation events over eastern China.

2 Data sets and analysis procedures

The dryness/wetness index (DWI) published by Chinese National Meteorological Administration (CNMA 1981) and recently extended by Zhang et al. (2003) is defined as a measure of rainfall in the main rainy season (Zhang 1988). The detailed descriptions can be found in some literature (Zhang 1988; Song 2000; Qian et al. 2003a, b). Its statistical properties such as consistency and persistence have been examined (Ronberg and Wang 1987; Zhang 1988). This five-

grade index is similar to the widely used standardized precipitation index (SPI; Hayes et al. 2000) (Table 1). We conducted a comparison of DWI and SPI in terms of occurrence probability of different precipitation conditions and actual SPI values calculated from observed precipitation data. The results showed that the DWI values of -2 (very dry), -1 (dry), 0 (normal), 1 (wet), and 2 (very wet) are approximately equal to the SPI values of less than -1.3 , -0.7 to -1.3 , -0.7 to 0.7 , 0.7 to 1.3 , and more than 1.3 , respectively.

The DWI dataset has 120 stations covering the whole of China. In the previous studies, this dataset was usually used as “point” data (e.g. Wang and Zhao 1981; Zhang 1988; Zhang and Crowley 1989; Yan et al. 1992; Qian et al. 2003b). The numbers or percentages of sites in dry/very dry and wet/very wet conditions were used as the criteria for detecting droughts and floods (e.g. Zhang and Crowley 1989; Song 2000; Qian et al. 2003b). Since the spatial distribution of sites is uneven and the spatial coverage represented by sites is different from each other, area-weighted average provides better estimate of regional climatic conditions of a given region (Zhai et al. 2005). The DWI for a site is assigned mainly based on evaluation of the historical records of counties in a given region, it thus is a “polygon” data rather than “point” data (Zhang 1988). To make best use of the spatial information of this data, we built a database of spatial coverage for these sites using the geographic information system (GIS) technique (Chapman and Thornes 2003). The spatial coverage for a region representing a site is defined by administration boundaries of counties. Each region includes about ten counties. It is roughly equal to one or two districts in the historical times of China (Zhang 1988). On the basis of this database, we developed an area-weighted average regional DWI to detect anomalous precipitation events. The first step was to estimate the area of a region representing a site, and area percentage of an interested division for each grade. Then we calculated average regional DWI for a given division using percent area as weights, i.e., $DWI_{\text{regional}} = 2P_{\text{vw}} + 1P_{\text{w}} + 0P_{\text{n}} - 1P_{\text{d}} - 2P_{\text{vd}}$. Here, P_{vw} , P_{w} , P_{n} , P_{d} , and P_{vd} are

Table 1 A comparison of dryness/wetness index with standardized precipitation index

Dryness/wetness index			Standardized precipitation index		
Classification	DWI value (SPI value)	Probability	Classification	SPI value	Cumulative probability
Very dry	-2 (< -1.3)	0.10	Extremely dry	-2 or less	0.0228
			Severely dry	-1.5 to -1.99	0.0668
Dry	-1 (-0.7 to -1.3)	0.25	Moderately dry	-1.0 to -1.49	0.1587
Normal	0 (-0.7 to 0.7)	0.30	Near normal	-0.99 to 0.99	0.6915
Wet	1 (0.7 to 1.3)	0.25	Moderately wet	1.0 to 1.49	0.8413
Very wet	2 (> 1.3)	0.10	Very wet	1.5 to 1.99	0.9332
			Extremely wet	2 or more	0.9986

area percentages of five climatic conditions (very wet, wet, normal, dry, and very dry) in a given division. This area-weighted average regional DWI was subsequently used to identify anomalous precipitation events in terms of occurrence probabilities of anomalous precipitation events in different categories (Table 1).

Here we chose North China (NC, 34–41°N, 107–120°E) and the middle and lower Yangtze River Valley (MLYRV, 26–34°N, 109–122°E) as two study divisions because the summer precipitation of these two divisions is highly related with the shift of the summer monsoon rain belt (Ding 1991; Samel et al. 1999). Luo et al. (2002) and Li et al. (2005) divided China into eight divisions. The boundaries of our two study divisions approximately equal to that of NC and Yangtze-Haihe River Basin in their climate division. NC and the MLYRV include 23 and 28 regions, respectively (Fig. 1). After identifying anomalous precipitation events, principal component analysis (PCA) on the data subsets consisting of anomalous precipitation events in different categories was employed to determine their dominant spatial modes. This technique has been used in previous studies of the spatial pattern of precipitation over eastern China (e.g. Wang and Zhao 1981; Qian et al. 2003b). Different from previous studies, which analyzed full data including “normal” years, our study focused on the identified anomalous precipitation events. Additionally, superposed epoch analysis (SEA; Grissino-Mayer 1995; Adams et al. 2003) was used to determine the relationship

between spatial patterns of precipitation and explosive volcanic eruptions.

3 Anomalous precipitation events

3.1 Identification

As expected, the time series of regional DWI for NC and the MLYRV show a normal or nearly normal distribution. Statistical test (the Shapiro–Wilks test) indicates that the time series of regional DWI for NC with mean, standard deviation, skewness, and kurtosis of 0.04, 0.63, -0.21 , and 0.04, fit a normal distribution at the 95% confidence level. The time series for the MLYRV with mean, standard deviation, skewness, and kurtosis of 0.09, 0.53, -0.35 , and 1.05 fit a Pearson-IV distribution at the 95% confidence level. Following the drought classification of SPI (Svoboda et al. 2002), which is widely used in the US and other countries, we selected 0.0228, 0.044, and 0.0919 as the occurrence probabilities of extreme, severe, and moderate droughts or floods for two divisions. According to these occurrence probabilities, the threshold values of regional DWI for anomalous precipitation events in different categories were then determined. They are -1.3 , -0.9 , and -0.5 for extreme, severe, and moderate droughts, whereas they are 1.1, 0.8, and 0.5 for extreme, severe, and moderate floods (Table 2).

Figure 2 shows the area percentage of NC in five climatic conditions and the area-weighted average regional DWI. In NC, 17, 27, and 53 cases of anomalous precipitation events were identified respectively as extreme, severe, and moderate floods, whereas 18, 32, and 60 cases were identified respectively as extreme, severe, and moderate droughts during the past 530 years. Among these flood years, 1964 with a regional DWI of 1.54 was the wettest year, when the highest summer rainfall in the period from 1951 to 2000 (40% more than that 50-year average) was recorded and 85.8% of NC suffered very wet conditions. Among the droughts, 1640 was the driest year. The regional DWI in 1640 was as low as -1.9 , and 93.6% of NC experienced very dry conditions. A noted hydrological event of that year was the desiccation of the Yellow River and some of its tributaries such as the Fenhe River, Xinhe River, and Yihe River (Tan 2003). The most recent extreme drought was in 1997, when there was no outflow of the Yellow River to the sea for 226 days (Qian and Zhu 2001; Zhai et al. 2005). About 700 km of the lower reach of the Yellow River dried up. Meanwhile, its major tributaries in its middle reach, including the Fenhe River, Xinhe River, Yihe River, Yanhe River, and Weihe River were desiccated. Observational data in the late twentieth century shows that summer rainfalls in NC was the lowest in 1997.

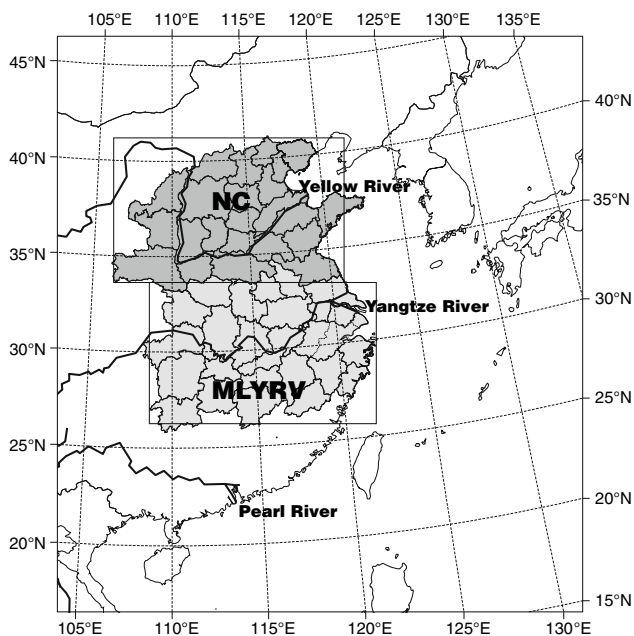
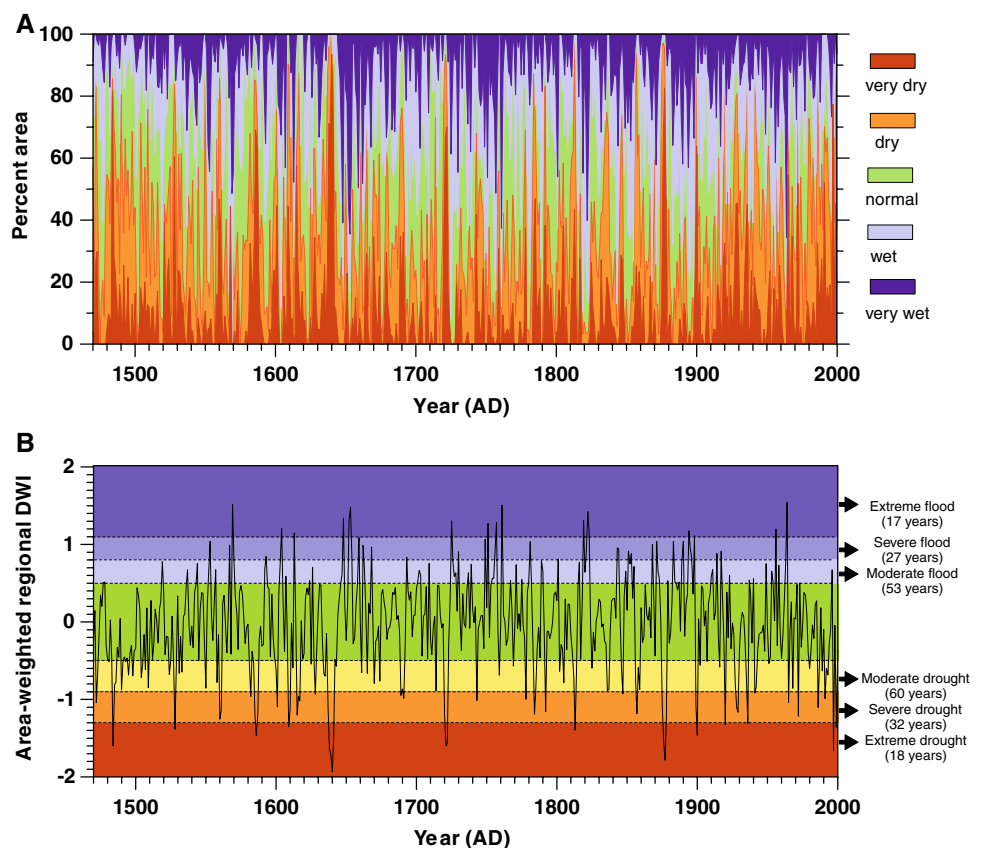


Fig. 1 Map showing the study area and two divisions, i.e. NC (34–41°N, 107–120°E), and the middle and lower Yangtze River valley (26–34°N, 109–122°E)

Table 2 A Summary of identified anomalous precipitation events over study region during the last five centuries

Anomalous precipitation events	North China		Regional DWI value	MLYRV	
	No. of years	Spatial coverage		No. of years	Spatial coverage
Extreme drought	18	Very dry (32.4–93.6%/63.9%) Dry (4.2–53.1%/28.3%)	<−1.3	7	Very dry (53.7–73.8%/64.3%) Dry (15.8–33.5%/25.7%)
Severe drought	32	Very dry (13.3–57.7%/37%) Dry (4.8–82.2%/41.2%)	−0.9 to −1.3	15	Very dry (30.7–62.1%/41.4%) Dry (16.7–50.6%/34.2%)
Moderate drought	60	Very dry (0–46.9%/18.4%) Dry (15.9–74.1%/43.6%)	−0.5 to −0.9	43	Very dry (0–38.5%/22.1%) Dry (5.9–80.1%/37.3%)
Moderate flood	53	Very wet (0–43.7%/19.7%) Wet (5.8–55.8%/36.7%)	0.5 to 0.8	68	Very wet (3.4–43.6%/20%) Wet (9.9–55%/33.2%)
Severe flood	27	Very wet (13.9–49.6%/33.6%) Wet (10.5–63.2%/36.1%)	0.8 to 1.1	27	Very wet (13.2–43.6%/29.7%) Wet (16.5–61.2%/38%)
Extreme flood	17	Very wet (32.5–85.8%/54.4%) Wet (8.2–68.7%/33.9%)	>1.1	11	Very wet (24.8–85.8%/54.4%) Wet (8.2–68.7%/33.9%)

Fig. 2 **a** Area percentages of NC in different climatic conditions, which are calculated on the total area of a given division, e.g. $P_{vw} = (\text{areas in very wet conditions})/(\text{total area}) \times 100\%$; **b** area-weighted regional DWI and identified anomalous precipitation events in terms of their occurrence probabilities used by US National Drought Mitigation Center (NDMC)

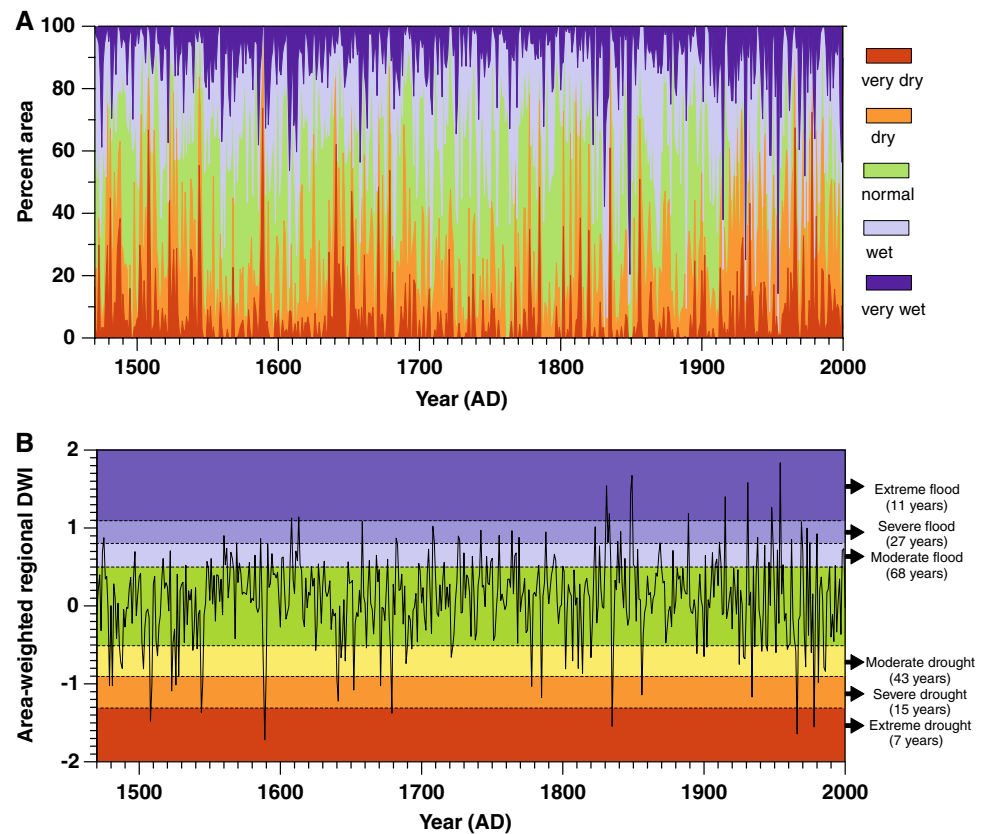


In the last four decades, only one moderate flood occurred in 1996, but there were two extreme droughts occurring in 1997 and 1999.

In the MLYRV, 11 extreme floods with regional DWI higher than 1.1 and seven extreme droughts with regional DWI lower than −1.3 were identified during the past

530 years (Fig. 3). Other identified anomalous precipitation events include 27 severe floods, 68 moderate floods, 15 severe droughts, and 43 moderate droughts. In the last five decades when the instrumental data was available, one extreme flood occurred in 1954 and two extreme droughts in 1966 and 1978. 1954 with the highest

Fig. 3 **a** area percentages of the MLYR in different climatic conditions; **b** area-weighted regional DWI and identified anomalous precipitation events in terms of their occurrence probabilities used by US NDMC



regional DWI of 1.84 was the wettest year in the past 530 years. Observational data indicated that the MLYRV recorded the highest summer rainfall in 1954, when summer rainfall was 80% more than the 50-year average from 1951 to 2000. In the extreme droughts of 1966 and 1978, the MLYRV recorded the first and second lowest summer rainfalls (45% less than the 50-year average). For the past 530 years 1589 was the driest year. This fact is supported by a major hydrological event recorded in Chinese historical documents. Taihu Lake, the third largest freshwater lake in China, dried up in 1589. In instrumental records from 1924 to 2000, the driest year was 1934 in the Taihu catchments, when Suzhou recorded 116 mm of summer rainfall (June–August) with a departure of -72% from the normal (420 mm). This drought caused the decline of the lake level and desiccation of channels on the shores of Taihu Lake, but the lake itself did not dry up.

A summary of identified anomalous precipitation events (Table 2) showed that NC was more prone to severe or extreme droughts and floods than the MLYRV during the past 530 years. The MLYRV was more vulnerable to moderate floods only. Our results also showed that in both divisions the area affected by a flood of any category was less than the area affected by a drought.

3.2 Temporal pattern

Here we used one decade as the time unit to calculate the frequency of anomalous precipitation events as did by Qian et al. (2003a). The Chi-squared test for Poisson distribution indicates that the frequencies of these events (moderate to extreme droughts and floods in both divisions) are not randomly distributed through time at the 99.9% confidence level. As shown by Fig. 4, there was a clear long-term trend or cycle in the frequency of anomalous precipitation events in both NC and the MLYRV. The severe and extreme floods or droughts seemed to occur in clusters more frequently.

In NC, a high frequency of severe and extreme floods occurred in the 1650s–1960s, 1750s–1760s, 1820s–1830s, and the 1890s. No severe or extreme floods happened in the period prior to 1560 nor in the last 30 years; and even the moderate floods were very few in these two periods. The highest frequency of floods occurred in 1871–1900 when NC experienced 14 floods in three decades. It is evident that 1580–1640 was the driest period in NC during the past 530 years. The highest frequency of severe and extreme droughts occurred in this period when NC experienced 15 severe or extreme droughts. The driest decade was 1631–1640 when NC experienced three extreme, one

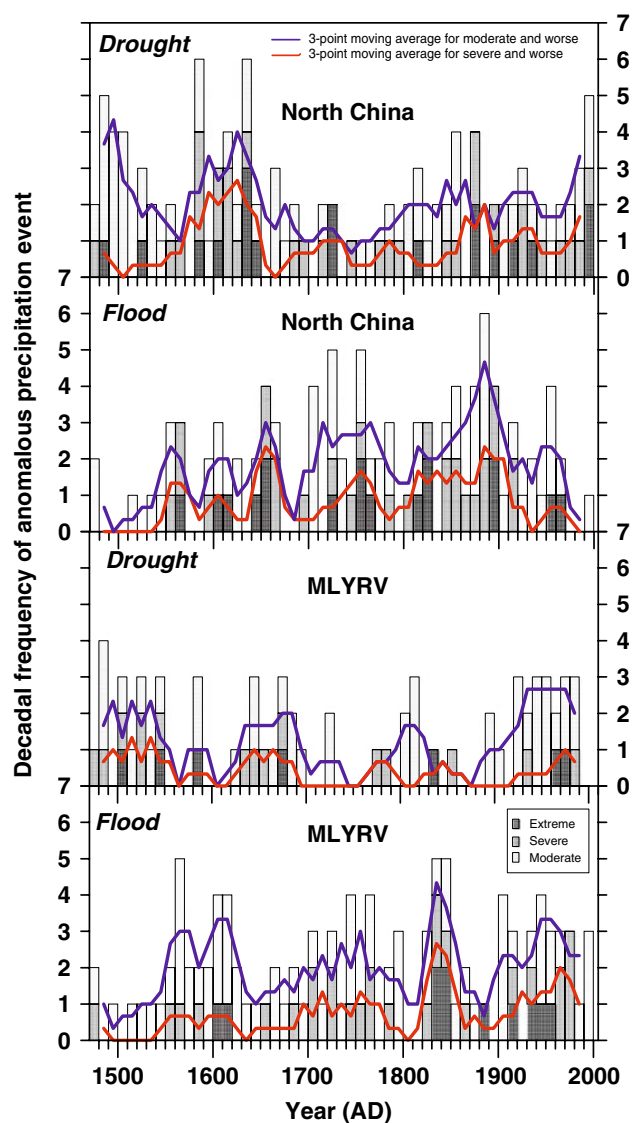


Fig. 4 Temporal variations in decadal frequency of anomalous precipitation events in NC and the MLYRV

severe, and two moderate droughts. The highest frequency of moderate droughts occurred in 1471–1510. NC saw few droughts in the 100 years from 1641 to 1740.

In the MLYRV, a high frequency of severe and extreme floods occurred in 1830–1850 and in 1950–1980. There were fewer floods in 1470–1550, 1620–1700, and 1800–1820. From 1830s to 1840s was the wettest period, when the MLYRV saw four extreme, three severe, and three moderate floods. The last few decades were an episode with low frequency of severe or extreme floods, although the frequency of moderate floods seemed to show an increasing trend in the 1990s. The MLYRV saw far fewer droughts than NC. Relatively high frequency of severe and extreme droughts occurred in 1500–1550, 1530–1580, and 1860–1900. The MLYRV did not experience any category

of droughts in the years 1551–1580, 1591–1620, 1701–1720, 1731–1770, and 1861–1870.

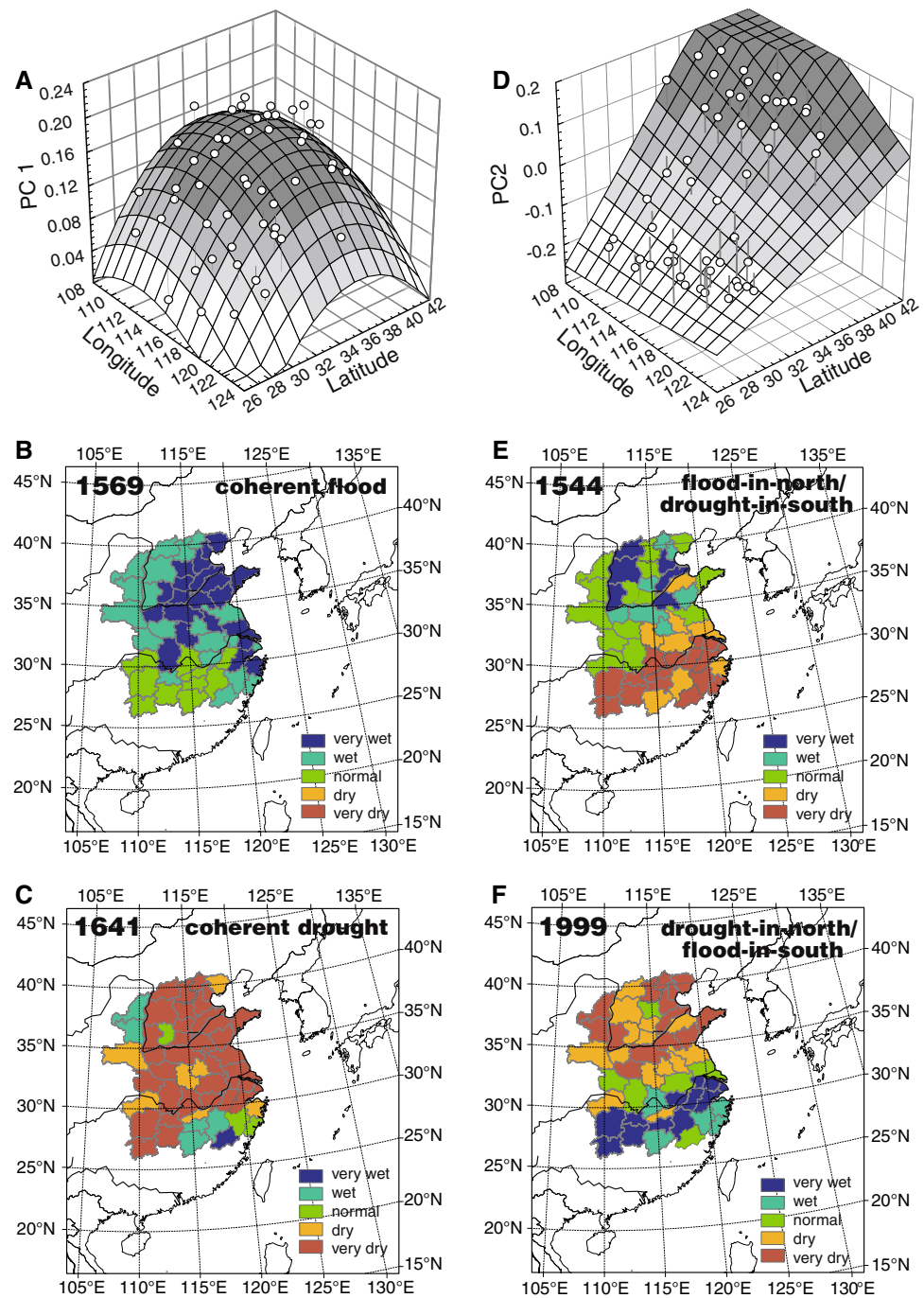
3.3 Spatial patterns

Based on the identified anomalous precipitation events, three datasets (A, B, and C) were extracted from the DWI data. Datasets A, B, and C were composed of 52 extreme cases, 102 severe cases, and 214 moderate cases, respectively. We conducted PCA on these three datasets. The main purpose of separate PCA on three datasets is to determine the difference of spatial patterns in anomalous precipitation events in different categories. The results of PCA showed that the spatial patterns revealed by the first three components were the same, however, the total variances explained by these components were different among these three datasets.

The first principal component (PC1) showed a coherent mode of spatial patterns (Fig. 5a). This PC explained 38, 27.6, and 20.7% of total variances in datasets A, B, and C. The coherent mode indicated that both NC and the MLYRV were subject to either floods or droughts at the same time. The year 1569 was a typical coherent flood case (Fig. 5b), when both the Yangtze River and Yellow River basins experienced floods. More than half the area of the MLYRV underwent wet and very wet conditions, whereas 51.4 and 48.6% of NC were in wet and very wet conditions. Similar coherent flood patterns were also found in the extreme flood cases of 1613, 1648, 1823, 1889, 1954, and 1956. 1641 was a typical coherent drought case (Fig. 5c). In this year, 74.1% of NC and 62.1% of the MLYRV were in very dry conditions. Similar coherent drought patterns also occurred in the extreme drought cases of 1528, 1640, 1721, 1722, 1877, 1900, and 1997.

The second PC indicated a north/south dipole mode of spatial patterns (Fig. 5d), i.e. When NC experienced a flood, the MLYRV experienced a drought. This mode accounted for 25.1, 16.0, and 12.5% of the total variances of datasets A, B, and C. The typical case with a flood in NC and a drought in the MLYRV was in 1544 (Fig. 5e). More than 50% of NC experienced wet and very wet conditions, and 55.1% of the MLYRV was having very dry conditions. The spatial patterns similar to that of 1544 were also found in the extreme cases of 1652, 1653, 1751, 1964, and 1978. Figure 5f shows a typical drought in NC and a flood in the MLYRV. In 1999, NC experienced an extreme drought. About 45.6 and 44.3% of NC were in dry and very dry conditions. The MLYRV witnessed a moderate flood in this year. 43.6% and 14.6% of the MLYRV were in wet and very wet conditions. Such patterns also occurred in 1586, 1609, 1915, 1931, and 1948.

Fig. 5 Spatial patterns derived from PCA on identified anomalous precipitation events. Coherent mode (a) indicated that both NC and the MLYRV suffered a flood (b) or drought (c), which accounted for 38% of total variance. North/south dipole mode (d) indicated that NC experienced a flood (e) or drought (f), whereas the MLYRV experienced opposite conditions. This mode accounts for 25% of total variance



The third PC only explained 5.7, 7.6 and 7.8% of the total variances of datasets A, B, and C, respectively. This component indicated a three-belt mode of spatial patterns, in which the northern part of NC and southern part of the MLYRV shared the same climatic conditions (either flood or drought), and the central part of the study area experienced the opposite conditions (not shown here). The typical years with either drought or flood in both the north and south and the opposite conditions in the central part of the study area were 1991 and 1973. In 1991, the northern part

of NC and the southern part of the MLYRV experienced a severe drought, whereas a severe flood occurred in the Huaihe River Valley. The climatic conditions in 1973 were opposite to that in 1991.

Similar modes of spatial patterns were also revealed by previous studies using full time series of selected sites (e.g. Wang and Zhao 1981; Qian et al. 2003a, 2003b). They found six patterns: (a) flood in most parts of eastern China; (b) drought in most parts of eastern China; (c) drought in the Yangtze River Valley and flood in other parts; (d) flood

in the Yangtze River Valley and drought in other parts; (e) flood in southern China and drought in northern China; and (f) drought in southern China and flood in Northern China. It is evident that our coherent mode corresponds to their patterns A and B whereas the dipole mode corresponds to their patterns C and D. And our three-belt mode is similar to their patterns E and F. We also conducted PCA on the full data set including normal years, the result is similar to that revealed by previous studies. The first three PCs accounts for 18.3, 12, and 6.7% of the total variance. Although the first three PCs showed similar modes in spatial patterns of precipitation, our obtained PCs from three data subsets explained more variances of the data, indicating that these three modes are more predominant in anomalous precipitation events than the others. A question arising from PCA on the data subsets is whether the difference in results between data subsets and full dataset results from increased uncertainty due to decreased sample size. To answer this question, we conducted PCA on randomly selected several data sets including normal years and anomalous events with the same sample size of dataset A. Results show that the total variance explained by the first three PCs changes slightly comparing with that of PCA on the full dataset. This fact indicates that coherent and dipole modes more predominant in anomalous precipitation events than the others are solid feature in spatial patterns of anomalous precipitation events.

As suggested by PCA, coherent and dipole modes were two dominant ones of spatial patterns of anomalous precipitation events. Of 52 extreme drought/flood cases, 42 cases belong to these two modes. If each of our study divisions (NC and the MLYRV) is considered as a whole, the spatial patterns of all anomalous precipitation events can be classified into these two modes including four patterns, i.e. coherent flood, coherent drought, flood-in-north/drought-in-south, and drought-in-north/flood-in-south by comparing the regional DWI of the two divisions. Figure 6 shows the frequency of the four spatial patterns classified this way. The Chi-squared test for Poisson distribution shows that these four spatial patterns are not distributed randomly through time on both the annual timescale and the decadal timescale at the 99.9% confidence level. They are clustered in time on the annual timescale (Fig. 6a), whereas clear temporal patterns were shown on the decadal and centennial time scales. Coherent floods dominated the eighteenth and nineteenth centuries (Fig. 6b) with the highest frequency in the 1880s, and the lowest frequency in the twentieth century. The twentieth century was characterized by a high frequency of coherent droughts (Fig. 6c) and dipole patterns (Figs. 6d, e). Both drought-in-north/flood-in-south and flood-in-north/drought-in-south happened most frequently in the twentieth century. Coherent droughts also occurred frequently in the seventeenth

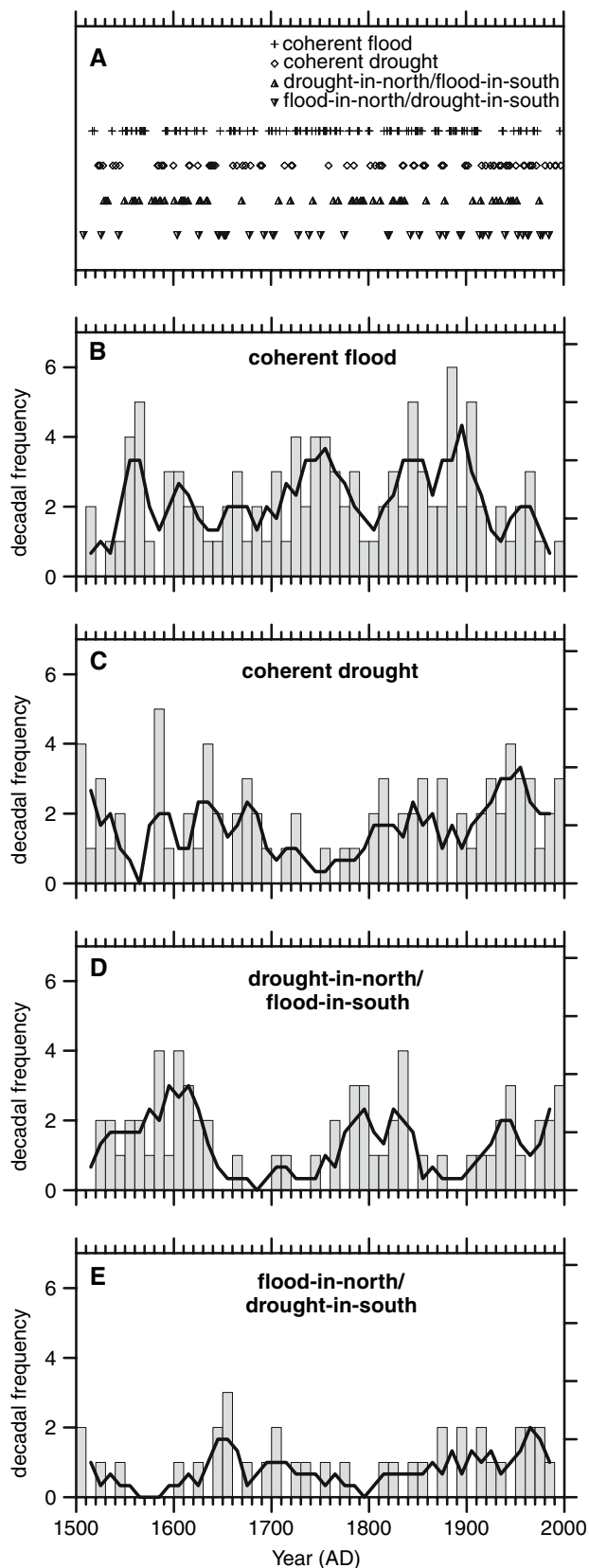


Fig. 6 Spatial patterns of anomalous precipitation events and their decadal frequencies in NC and the MLYRV during the past five centuries

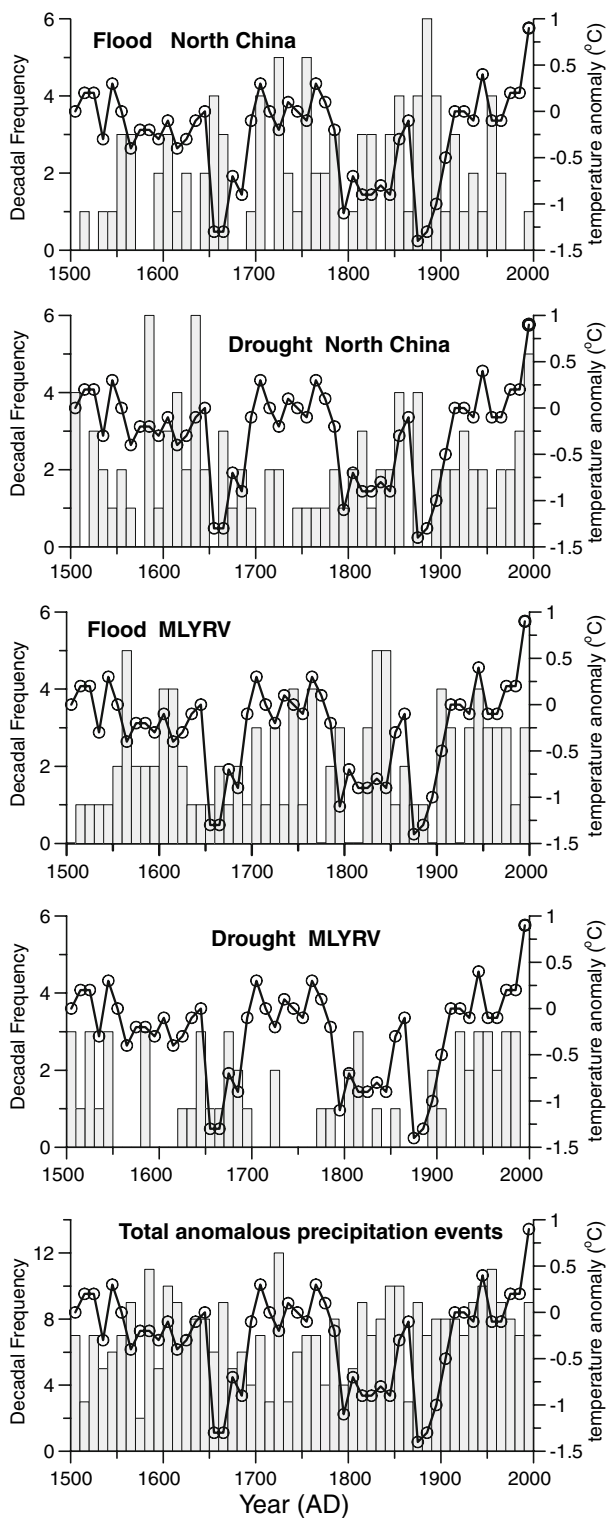


Fig. 7 A comparison of the winter half-year temperatures over eastern China and the decadal frequency of anomalous precipitation events (including moderate to extreme droughts or floods) in NC and the MLYRV. Lines with empty circles denote decadal winter half-year temperatures, and bars denote the decadal frequency of anomalous precipitation events (the Chi-squared test for Poisson distribution indicates that they are not randomly distributed through time at the 99.9% confidence level)

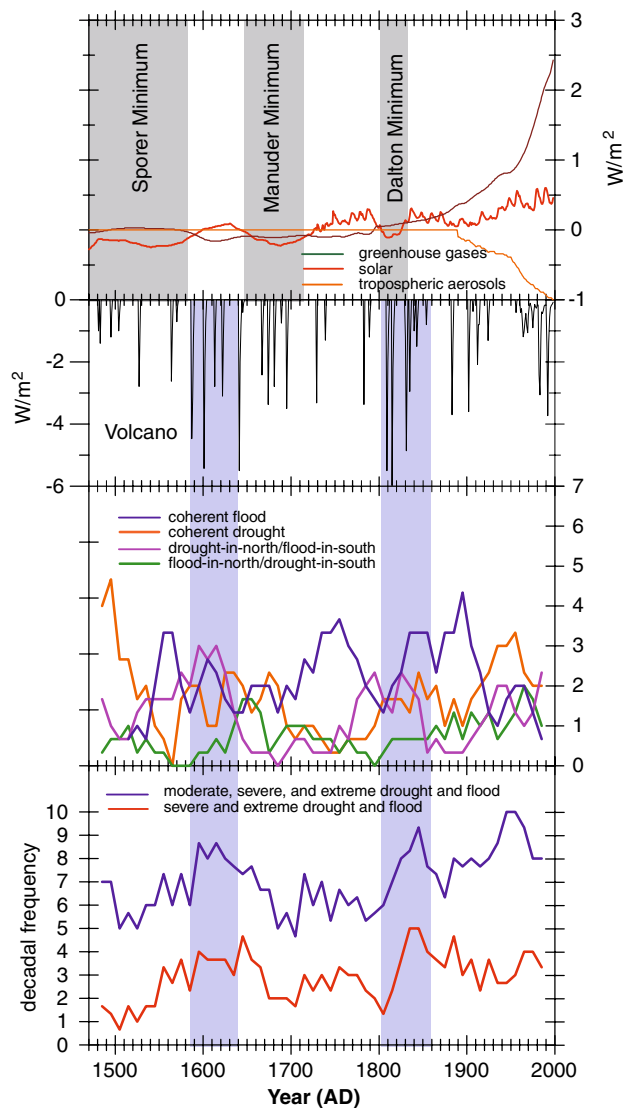


Fig. 8 A comparison of decadal frequency (three-decade moving average) of anomalous precipitation events with climate forcings

century. In the sixteenth century, its first half was dominated by coherent droughts and dipole patterns; coherent droughts were then replaced by coherent floods in the following two decades; its last three decades were dominated by coherent droughts and dipole patterns again.

4 Discussions and conclusions

A number of studies of observation data indicated that the summer rainfall over eastern China was associated with a range of factors. They include the strength of the summer monsoon (Ding 1991; Qian et al. 2003b), the strength and position of the subtropical high (Ding 1991; Wang et al. 2000a, b; Chang et al. 2000), the phases of the ENSO and PDO (Wang et al. 2000a, b; Mantua and Hare 2002;

Table 3 Correlations among decadal anomalous precipitation events over eastern China, solar forcing, and major volcanic eruptions

Events	NC		MLYRV		EC (total)	Spatial pattern					
	Drought	Flood	Drought	Flood		CF	CD	NDSF	NFSD	CM	DM
Solar ^a	-0.03	0.15	0.07	0.34 ^c	0.33 ^c	0.14	-0.01	0.15	0.20	0.14	0.29 ^c
Volcanic ^b	-0.28 ^c	-0.20	0.30 ^c	0.19	0.32 ^c	-0.07	0.26 ^d	0.12	0.12	0.20	0.21

CF coherent flood, *CD* coherent drought, *NDSF* drought in north/flood in south, *NFSD* flood in north/drought in south, *CM* coherent mode, *DM* dipole mode

^a Non-overlapping 10-year average

^b Non-overlapping 10-year count of major volcanic eruptions based on volcanic forcing data from Jones and Mann (2004)

^c Significant at the 95% confidence level (2-tailed)

^d Significant at the 90% confidence level

Hu et al. 2005; Li et al. 2005), winter and spring snow depth over the Tibetan Plateau (Qian et al. 2003c; Wu and Qian 2003; Zhang et al. 2004), volcanic eruptions (Zhang and Zhang 1994; Bradbury 2006), and tropical sea-surface temperatures and land surface conditions such as surface air temperature and soil moisture (Huang et al. 2003; Qian et al. 2003b; Yang and Lau 2004). These factors are generally interrelated with each other and also related to climate forcings. Here we discuss relationships of the temporal and spatial patterns of anomalous precipitation events with available reconstructions of climatic proxy data and climate forcings.

The connection between temperature change and dryness/wetness condition in China has been studied using proxy data and instrumental data (e.g. Zheng and Feng 1986; Guo and Sha 1996; Shi et al. 1999; Qian and Lin 2005). Results from proxy data indicated that an increased frequency of drought generally occurred during cold periods in China although there were some exceptions, and that both drought and flood happened frequently in some cold periods (Zheng and Feng 1986; Shi et al. 1999). Observational data showed that a warm-dry climate state occurred in NC whereas both cool-wet and warm-wet climate states were found in the MLYRV (Guo and Sha 1996; Qian and Lin 2005). A time series of winter half-year (October–April) temperatures on the decadal time scale over eastern China for the past 500 years is available now (Ge et al. 2003). This time series was reconstructed from phenological cold/warm events recorded in Chinese historical documents.

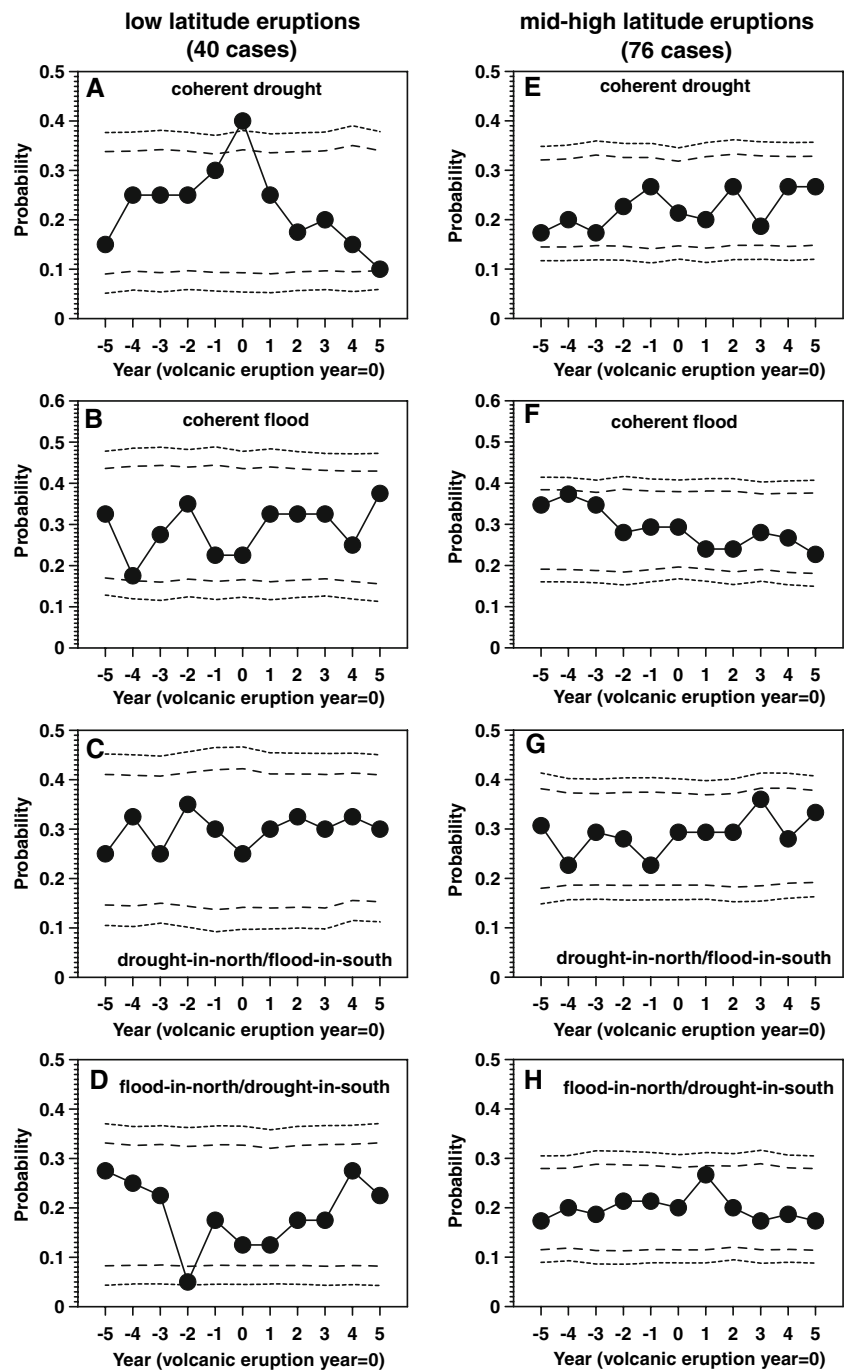
A comparison between winter half-year temperatures and decadal frequency of anomalous precipitation events (Fig. 7) showed some associations between them. The high frequency of floods in NC was generally associated with the cold period over eastern China. Floods occurred frequently in NC during two coldest periods of 1650–1770 and 1870–1900, especially the late period when NC experienced the highest frequency of floods. There were fewer floods in NC during warm periods. Although

relatively high frequency of floods also occurred in a warm period from 1700 to 1790, two peaks of flood frequency existed in two intervals of temperature decline. The variation of flood frequency in the MLYRV was opposite to NC on the decadal time scale. Fewer floods occurred in cold periods and more in warm periods, although there are some exceptional intervals such as 50 years prior to 1550 and 30 years from 1820 to 1850. The former in a warm period saw fewer floods, whereas the latter in a relatively cold period witnessed more floods.

The frequencies of droughts in NC showed an opposite trend to floods. More droughts occurred during warm periods. Again, there was a marked exception of the warm period from 1700 to 1790, which saw far fewer droughts. There was no clear correlation between temporal patterns of drought frequency in the MLYRV with winter half-year temperatures over eastern China. Either high or low drought frequencies occurred in warm periods. The correlation between temperature and the frequency of total anomalous precipitation events including floods and droughts was not significant on the decadal time scale over eastern China, although whole China saw more anomalous precipitation events during the cold periods as suggested by previous studies (e.g. Zheng and Feng 1986; Shi et al. 1999).

This comparison revealed two interesting facts. The first fact is that floods occurred frequently during cold intervals and more droughts during warm period in NC. This fact is consistent with the observational climate state in the last five decades (Guo and Sha 1996; Qian and Lin 2005). The second fact is that the frequency and spatial patterns of anomalous precipitation events were different in the two warm periods of the eighteenth and twentieth centuries. Both NC and the MLYRV experienced far fewer droughts and more floods in the eighteenth century, whereas much more droughts occurred in the twentieth century. This fact indicates that the connection between temperature change and anomalous precipitation event is not persistent and it changes through time.

Fig. 9 Superposed epoch analysis showing the relationship between the occurrence probability of spatial patterns of precipitation over eastern China and explosive volcanic eruptions. Bootstrapping procedures were used to assess the statistical significance of occurrence probability above and below the mean. The *dashed* and *dotted lines* represent confidence intervals of 95 and 99% derived from 1000 Monte Carlo simulations. The data source of explosive low-latitude and mid-high latitude volcanic eruptions ($VEI \geq 4$): Briffa et al. 1998; Adams et al. 2003; and <http://www.volcano.si.edu/world/largeeruptions.cfm>. Forty explosive low-latitude volcanic eruptions include: 1586, 1593, 1600, 1640, 1641, 1661, 1665, 1674, 1680, 1720, 1745, 1756, 1760, 1761, 1764, 1768, 1791, 1793, 1803, 1808, 1812, 1813, 1814, 1815, 1818, 1823, 1835, 1869, 1884, 1899, 1902, 1911, 1917, 1943, 1951, 1963, 1968, 1982, 1990, 1991. Seventy-six cases of mid-high latitude volcanic eruptions are not listed here



Some previous studies indicated the occurrence of a quasi-centennial oscillation in summer rainfall over eastern China (e.g. Zhu and Wang 2001; Qian et al. 2003b). This oscillation might have been associated with the solar forcing fluctuation on the quasi-centennial time scale (Gleissburg cycle). The frequency of anomalous precipitation event over eastern China showed a similar oscillation (Fig. 8). The correlation between decadal anomalous precipitation events and non-overlapping 10-year averages of solar forcing is statistically significant at the 95% confidence level

(correlation coefficient is 0.33), indicating that more anomalous precipitation events occurred during the periods of high solar forcing than low solar forcing. Among these events, floods in the MLYRV and dipole mode are significantly correlated with solar forcing (Table 3). Furthermore, the peaks of anomalous precipitation event mainly occurred at these transitions from low to high solar forcing (e.g. 1590–1610, 1715–1735, and 1830–1840).

Figure 8 also shows a marked difference in both the frequency and spatial patterns of anomalous precipitation

events between the twentieth century when the anthropogenic climate forcing dominated and other centuries when the natural climate forcing dominated. The highest frequency of anomalous precipitation events occurred in the late twentieth century. More coherent droughts and dipole patterns existed then. Our results support the hypothesis that the climate effects of tropospheric aerosols would cause increased droughts in NC and increased floods in the MLTRV (Menon et al. 2002). On the other hand, the high frequency of coherent droughts mainly occurred in the twentieth century and the early seventeenth century. The former is probably attributed to either climate effects of human-induced land cover changes (Fu 2003) or tropospheric aerosols. The latter might have been related to volcanic eruptions.

As mentioned above, volcanic forcing is another major factor affecting summer rainfall over eastern China. Our results showed that the peaks in the frequency of anomalous precipitation events occurred in active periods of volcanic eruption (e.g. 1580–1650 and 1810–1860), and fewer anomalous precipitation events occurred in both NC and the MLYRV during the sixteenth and eighteenth centuries, when less volcanic eruptions occurred. Statistical analyses indicated that the correlation between decadal anomalous precipitation events and volcano eruption events is statistically significant at the 95% confidence level (correlation coefficient is 0.31, Table 3). Our analyses also showed a significant correlation between volcanic eruption events and droughts in both NC and the MLYRV. Among four spatial patterns, only coherent drought is significantly correlated with volcanic eruption events at the 90% confidence level. A typical case of coherent drought was in 1641. Several large volcanic eruptions happened in 1640 and 1641 (e.g. Tungurahua, Ecuador, 1640, VEI = 4?; Llaima, Chile, 1640. February, VEI = 4; Komaga-Take, Japan, 1640 July, VEI = 5; Kelut, Indonesia, 1640, VEI = 4?; and Parker, Philippines, 1641 January, VEI = 5?). To further assess what spatial pattern of precipitation is statistically significant signal in response to explosive volcanic eruption, we employed the SEA, a statistical method used to resolve significant signal to noise problem (Adams et al. 2003), to examine if the occurrence probability of four spatial patterns during and after explosive low and mid-high latitude volcanic eruptions is significantly different the mean (Fig. 9). During the explosive low-latitude volcanic eruption year, the occurrence probability of coherent drought is significantly higher than the mean at the 99% confidence level, indicating a statistically significant connection between explosive volcanic eruptions and subsequent coherent drought over eastern China. None of 5 years after volcanic eruptions were significantly different from the average occurrence probability of coherent drought (Fig. 9a), suggesting that explosive low-latitude

eruptions affect the spatial pattern of precipitation over eastern China most in the eruption year. The mean values of occurrence probability for other three patterns are not significantly different from their means during and after explosive low-latitude volcanic eruptions (Fig. 9b–d), indicating no significant connection between explosive low-latitude eruptions and other three spatial patterns. The SEA results also show that the occurrence probability of all four spatial patterns does not depart significantly from the mean during and after explosive mid-high latitude volcanic eruptions (Fig. 9e–h), indicating no significant connection between spatial patterns of precipitation over eastern China and explosive mid-high latitude volcanic eruptions. Having analyzed modeled and observed data, Robock and Liu (1994) noted that tropical precipitation for 1–2 years following volcanic eruptions was reduced. They attributed this to reduced evaporation caused by tropospheric cooling. The statistically significant connection between explosive low-latitude volcanic eruptions and droughts over eastern China suggested by our results seems to support their hypothesis.

In summary, our study showed the following for the lines of our focuses mentioned in the introduction:

1. On the decadal timescale, the high frequency of severe and extreme floods occurred in 1650–1660s, 1750–1760s, 1820s and 1890s, whereas the period from 1580 to 1650 and the 1990s witnessed more severe and extreme droughts in NC. The highest frequency of severe and extreme floods occurred in 1830–1850 and 1950–1980 in the MLYRV. The MLYRV experienced far fewer droughts and more floods (especially moderate floods) than NC in the past five centuries.
2. Coherent floods dominated the eighteenth and nineteenth centuries, whereas the lowest frequency of coherent floods occurred in the twentieth century. The spatial patterns of anomalous precipitation events in the twentieth century were mainly coherent droughts and dipole patterns, i.e. drought-in-north/flood-in-south and flood-in-north/drought-in-south. Coherent droughts also occurred frequently in the seventeenth century.
3. The high frequency of anomalous precipitation events occurred at periods of (a) high solar forcing, (b) active periods of volcanic eruption, and (c) the twentieth century when anthropogenic forcing emerged as dominant forcing. The dominant spatial patterns of anomalous precipitation events associated with large low-latitude volcanic eruptions were coherent droughts. The increased coherent droughts and dipole patterns in the twentieth century were likely attributed to the tropospheric aerosols and human-induced land cover changes.

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