

## Precipitation Variability and Extreme Events in Eastern China during the Past 1500 Years

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### ABSTRACT

A proxy precipitation index dataset for the period 501 - 2000 over eastern China (east of 105°E; 25 - 40°N approximately) was statistically derived from three existing datasets, which were reconstructed based on Chinese historical documents and instrument measurements. The index was then used to analyze decadal-to-centennial precipitation variability with a focus on three sub-regions, North China Plain (34 - 40°N approximately), Jiang-Huai area (31 - 34°N approximately) and Jiang-Nan area (25 - 31°N approximately). In addition, major drought/flood events considering severity, persistency, and spatial coverage were also identified. On the centennial time scales, precipitation variation in eastern China exhibited four dry epochs (500s - 870s, 1000s - 1230s, 1430s - 1530s and 1920s - 1990s) and three wet epochs (880s - 990s, 1240s - 1420s and 1540s - 1910s), with multi-decadal dry/wet fluctuations within each epoch. However, variation showed strong regional differences, for example, opposite trends were found in the Jiang-Nan area and Jiang-Huai area during the 11 - 13th centuries and in the North China Plain and Jiang-Nan area since the 16th century. The data also showed 16 drought and 18 flood events in eastern China, with the most severe drought event occurring in 1634 - 1644. Droughts dominated in the 12 - 14th centuries, but since the middle of the 17th century eastern China has been more subject to flooding. The severity of floods during the 20th century was comparable in intensity to historical times, but the droughts were usually less severe.

(Key words: Precipitation variability, Extreme events, Eastern China, Past 1500 years)

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## 1. INTRODUCTION

Studying climatic variability in historical times provides a valuable time perspective for identifying pre-industrial variability, and presents a complete picture of climate variation (Eddy 1992; Duplessy and Overpeck 1994; Jones et al. 2001; Bradley et al. 2003). Precipitation variability dominates both water resource supply and the occurrence of droughts and floods, and has a great impact on agricultural, economic and social activities. Recently several studies (Cook et al. 1999; Hughes and Funkhouser 1999; Laird et al. 1996; Stahle et al. 2000; Verschuren et al. 2000; Woodhouse and Overpeck 1998) indicated that precipitation variability on local and regional scales observed during the 20th century could not fully represent the range of precipitation variation in pre-industrial times.

As an area strongly influenced by the Asian Monsoon system, eastern China has a characteristically large precipitation variability, which leads to higher frequencies of drought and flooding as well as severe and persistent droughts and floods. For example, in the 20th century the data from The Disaster Center (2005a, b) show that of the 100 deadliest natural disasters, 23 occurred in China, 12 of which resulted in severe droughts (2-times) or extreme floods (10-times). Of the 100 most expensive natural disasters around the world in the 20th century, 17 occurred in China, and 11 of them were due to extreme flooding. Moreover, severe and persistent droughts in the 1920s in northern China and their related famines, epidemics and banditry caused more than 4 million deaths (Liang et al. 2003, 2004). In order to evaluate the severity, duration, and extent of twentieth-century droughts and floods in the context of a long history, we present here an analysis on proxy-precipitation datasets derived from Chinese historical documents over eastern China for the past 1500 years. Moreover, this study will also lead to a better understanding of the long-term pattern of precipitation change on a regional scale and Asian Monsoon circulation, which will be helpful for climate projection in the future.

China possesses a rich legacy of documents describing climatic events and their impacts on agriculture and other human activities in historical times, particularly for the last few millennia (Chu 1926, 1973; Zhang and Gong 1980; Zhang 1982; Wang and Zhang 1988; Ge and Zhang 1990). These documents have been used to construct precipitation proxies such as local dry/wet (or drought/flood) grades for 1470 ~ 1979 (CMA 1981), a regional dry/wet dataset for 960 ~ 1992 (Zhang et al. 1997) and regional moisture conditions proxies for the last 2000 years (Gong and Hameed 1991). Based on these proxy data, a considerable number of analyses of spatial and temporal patterns over China have been performed (e.g., Wang and Zhao 1981; Zheng and Feng 1986; Ronberg and Wang 1987; Zhang and Crowley 1989; Jiang et al. 1997; Qian et al. 2003). However, these studies did not provide a very clear understanding of the frequency of severe droughts and floods during the twentieth century in the context of the last 2000 years, i.e., whether droughts and floods of even greater magnitude had occurred. In this study, we will focus on the reconstruction of regional long-term precipitation variability by combining several existing datasets, and analysis of these data to identify extreme events of persistent drought and flooding.

## 2. A BRIEF DESCRIPTION OF THE DATASET

During the past few decades, a group from the Institute of Geographic Sciences and Natural Resources Research in the Chinese Academy of Sciences (IGSNRR/CAS) and their collaborators have systematically collected and extracted climatic information from historical documents in China. By careful scrutiny of all of the original descriptions, a new dataset, the 48-stations (Fig. 1) yearly drought/flood grade series in eastern China (east of 105°E, 25 - 40°N approximately) is constructed. Note that this new dataset is a combination of three separate sub-datasets. The first is the drought/flood grading for 63 stations in the period 137 BC to 1469 AD derived from 22567 pieces of historical drought/flood descriptions extracted from ancient Chinese writings (Zhang 1996). The second is the dry/wet dataset for 85 stations from 1470 to 1950 based on the statistics of drought/flood counties extracted from local gazettes and historical drought/flood archives (Zheng et al. 1993). The third is drought/flood grading since 1951 for the same stations based on individual station precipitation records. The combination of three separate sub-datasets is calibrated by Fisher linear discriminance and Bayesian estimate with the ideal grade frequency criteria of 10% (grade 5, severe drought),

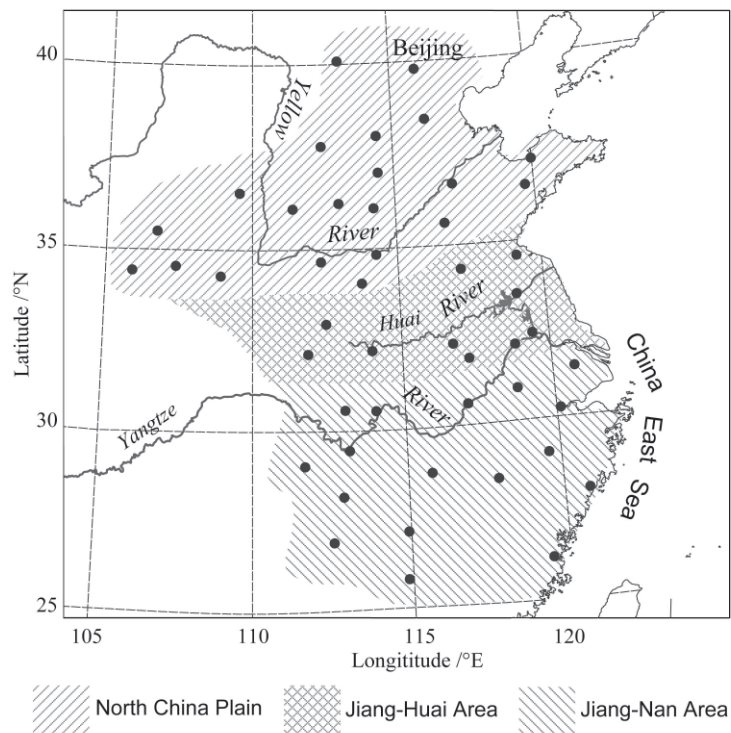


Fig. 1. Location of stations with drought/flood grade data and sub-region divisions.

20% (grade 4, drought), 40% (grade 3, normal), 20% (grade 2, flood), and 10% (grade 1, heavy flood) (Zhang 1996).

Note worthily, several century-long and large-scale proxy precipitation datasets had also been achieved before using Chinese historical documents. CMA (1981) used local gazettes and other historical writings from provinces and counties to reconstruct a dataset of 120-station dryness/wetness grades (1-very wet, 2-wet, 3-normal, 4-dry, 5-very dry) for 1470 - 1979 year by year, by using a methodology of interpreting a qualitative description to a quantitative grade based on the meaning of descriptive terms. Zhang et al. (1997) used the same approach to establish six regional series of dry/wet grading for 960 ~ 1992 from the Lower Yangtze Valley to the North China Plain. Gong and Hameed (1991) reconstructed three regional-mean moisture index series in East China for the last 2000 years, by accounting for the number of reported flood and drought events in every 5-year interval. Compared with the reconstructed datasets of CMA (1981) and Zhang et al. (1997), our new dataset has a longer temporal coverage extending to 137 BC. Compared with the regional moisture index series reconstructed by Gong and Hameed (1991), our dataset has a higher time resolution. Even so there exist a lot of missing records in this dataset before 1470 because of the limits of original historical drought/flood records (Man 2000a). This dataset provides a useful proxy for the study of precipitation change during the last 2000 years, and it also works well for analysis of the stages of climatic evolution (Zhang et al. 1994) and centennial change of drought/flood spatial patterns (Zheng et al. 2001) in eastern China for the last 2000 years.

### 3. PRECIPITATION VARIABILITY RECONSTRUCTION

#### 3.1 Definition of Dry-Wet Index

From the study on the distribution of drought/flood records in historical times (Man 2000a), it is known that the yearly drought/flood-grade data before 1470 had an uneven temporal distribution, i.e., earlier data is less available, later data is more complete (see also Fig. 2b). This apparent uneven temporal distribution is mainly attributed to the increased availability of surviving historical writings from later years (see Man 2000a for details). To avoid the effect of data missing and maintain a homogeneous database, a dry-wet index is developed here to analyze the long-term pattern of precipitation change.

Let  $G_{ij}$  be the drought/flood grade in year  $i$  at station  $j$

$$G_{ij} = \begin{cases} 0 & \text{when the grade is not available} \\ k & \text{when the grade is } k \end{cases},$$

and let

$$F_{ij}^T = \begin{cases} 0 & \text{when } G_{ij} = 0 \\ 1 & \text{when } G_{ij} \neq 0 \end{cases} \quad \text{and} \quad F_{ij}^k = \begin{cases} 0 & \text{when } G_{ij} \neq k \\ 1 & \text{when } G_{ij} = k \end{cases},$$

where  $k$  is the grade of drought/flood, i.e.,  $k = 5, 4, 2, 1$  represents severe drought, drought, flood, and heavy flood respectively; and  $T$  means the collection of drought/flood grades, i.e.,  $T = \{5, 4, 2, 1\}$ . Then for a  $t$ -year interval ( $t$  is set as 10 in this study because we focused on long-term precipitation change on a inter-decadal scale) starting at year  $s$ , the average of the frequency that grade  $k$  appears in the region will be:

$$P_{st}^k = \frac{\sum_{i=s}^{s+t-1} \sum_{j=1}^J F_{ij}^k}{\sum_{i=s}^{s+t-1} \sum_{j=1}^J F_{ij}^T},$$

where  $J$  is the total number of stations for the region. Note that the length of time interval  $t$ , will not affect the tendency of dry/wet, although it may affect the time resolution of the series.

Finally, define the dry-wet index as:

$$Dw_{st} = 2 \cdot p_{st}^1 + p_{st}^2 - p_{st}^4 - 2 \cdot p_{st}^5 \quad (1)$$

From this definition it is easy to see that when  $Dw_{st} > 0$ , it is wet; when  $Dw_{st} < 0$ , it is dry. Furthermore the absolute value  $|Dw_{st}|$  indicates the degree of dry-wet severity, i.e., a larger value indicates a greater severity.

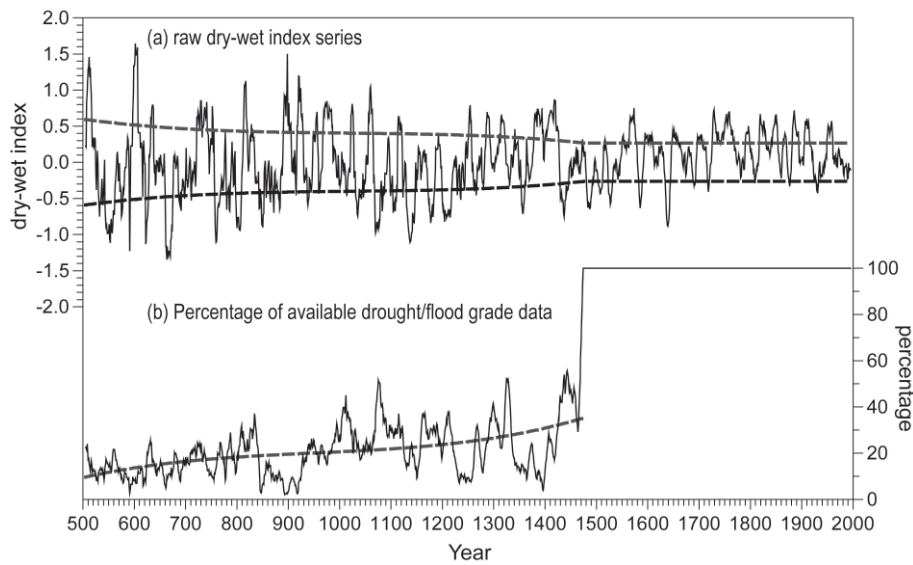


Fig. 2. Comparison of the raw dry-wet index series and the change of percentage of the available drought/flood grade data.

### 3.2 Construction of the Dry-Wet Index Series

Using the definition and equation above, the raw dry-wet index series for the whole of eastern China is shown in Fig. 2a. Because of too much missing drought/flood-grade data before 500 AD for all 48 stations, this series starts only from 500 AD. Even so, there still exists a decreasing trend in the magnitude of the series variance from 500 to 1470. This is caused by the increasing trend (Fig. 2b) of the available drought/flood-grade data during 500 - 1470. After 1470 the drought/flood-grade data for all 48 stations is available, and the magnitude of the series variance does not show a decreasing trend. To eliminate this decreasing trend effect we use a polynomial fitting equation to fit the effect trend curve. Because the detrended series is developed by dividing the raw dry-wet values by the fitted trend values, the detrended dry-wet index series (Fig. 3a) is a normalized series. Thus the detrended dry-wet index series can be used to represent the long-term precipitation change.

Moreover, to present regional differences in long-term precipitation change, we divided the study area, eastern China, into 3 sub-regions based on their physical geography (see also Fig. 1). The detrended dry-wet index series for these 3 sub-regions are shown in Figs. 3b - d. Sub-region I is the North China Plain (34 - 40°N approximately) with 21 stations. Sub-region II is the Jiang-Huai area (31 - 34°N approximately) with 10 stations. Sub-region III is the Jiang-Nan area (25 - 31°N approximately) with 17 stations. The mean values for the whole period are -0.13 (North China Plain), 0.16 (Jiang-Huai area) and 0.35 (Jiang-Nan area) respectively, and the variances of these 3 sub-regional series are all 1.0. This is because the climate in the North China Plain is characterized by sub-humid conditions with more drought than flooding, while the Jiang-Huai area and the Jiang-Nan area are characterized by humid conditions with more flooding than drought, and the climate of the Jiang-Nan area is also more humid with a relatively high frequency of flooding.

To examine the rationality of the dry-wet index series we compared the three sub-regional dry-wet index series with the following independent data: instrumental observation of precipitation in Beijing (1870 ~ 1950), Nanjing (1905 ~ 1936) and Shanghai (1873 ~ 1950), as well as reconstructed precipitation (1736 ~ 1950) in the middle and lower reaches of the Yellow River derived from snow and rainfall records in the archives of the Qing Dynasty (Zheng et al. 2005). The comparison between the sub-regional dry-wet index series and these independent data (for matching the time resolution of the dry-wet index series, all data here are calculated on a 10-year running mean), shown in Fig. 4, indicates that the sub-regional dry-wet index could provide a reasonable representation of precipitation change for the calibrated period. The correlation coefficients between the dry-wet index and the precipitation are 0.66 (Sub-region I and Beijing 1870 ~ 1950), 0.84 (Sub-region II and Nanjing 1905-1936), 0.78 (Sub-region III and Shanghai 1873 ~ 1950), 0.66 (Sub-region I and the middle and lower reaches of the Yellow River 1736 ~ 1950), respectively.

In addition, the general comparison between the dry-wet index and the reconstructed annual precipitation series at Nanjing, Suzhou and Hangzhou (Zhang and Wang 1989; Zhang et al. 2005), as well as the series on rainfall amounts in Meiyu seasons over the lower Yangtze region (Zhang and Wang 1991) during the 18th century shows that all of them experience approximate fluctuations. In which both the dry-wet index in the Jiang-Huai area and the

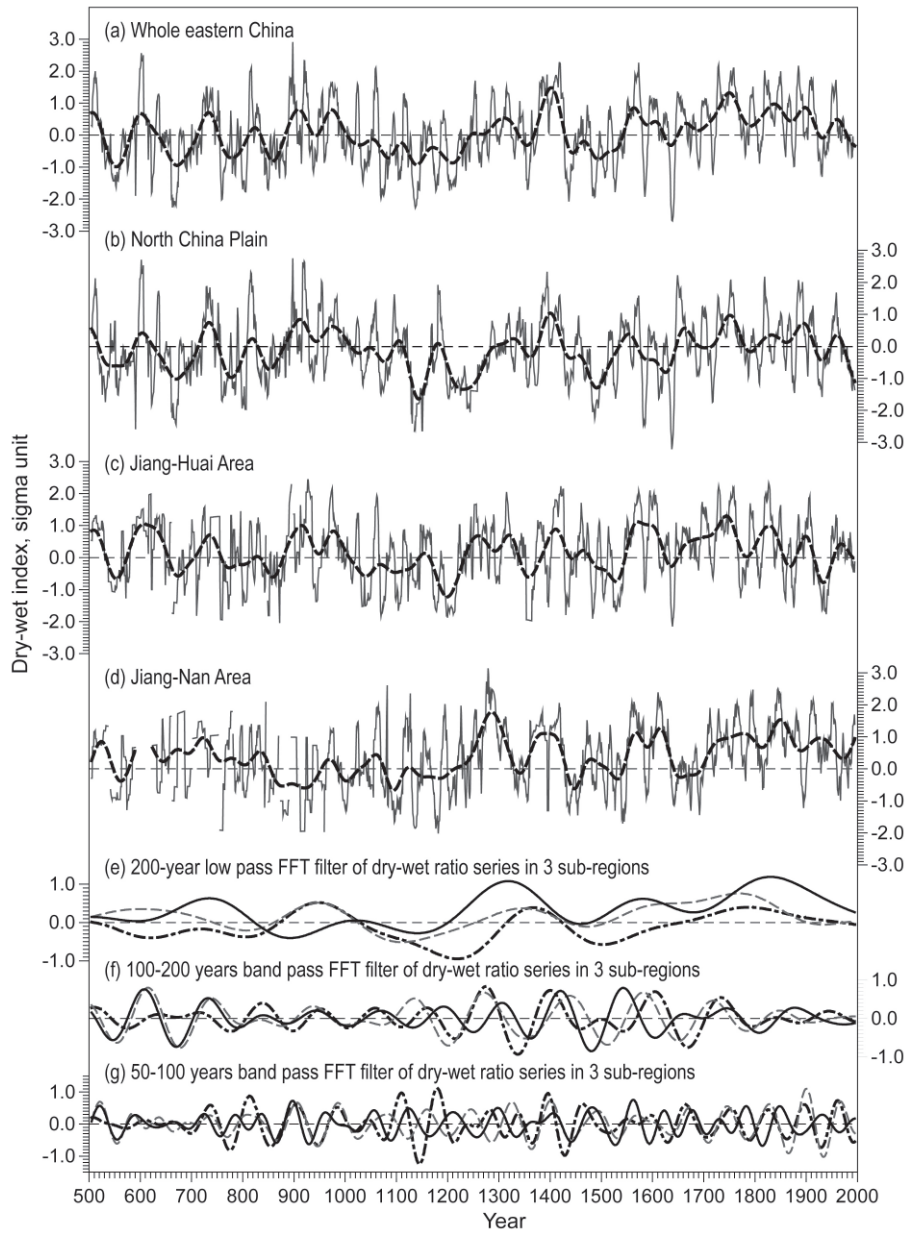


Fig. 3. Precipitation variation and its regional differences in eastern China during 500 - 2000. (a - d): Standardized dry-wet index series (gray line) and the 30-year FFT filter smoothing (Bold dash); (e - f): FFT filter signals of sub-regional dry-wet index series. Bold dash-dot: North China Plain. Thin gray dash: Jiang-Huai area. Solid: Jiang-Nan area.

annual precipitation at Nanjing experience two short wet periods around 1730 and 1755, as well as an apparent dry period in 1760s - 1780s. The dry-wet index in the Jiang-Nan area and annual precipitation at Suzhou and Hangzhou, as well as precipitation amounts in Meiyu seasons over the lower Yangtze region all present two short wet periods around 1730 and 1765, as well as two dry periods in 1735 - 1755 and around 1780.

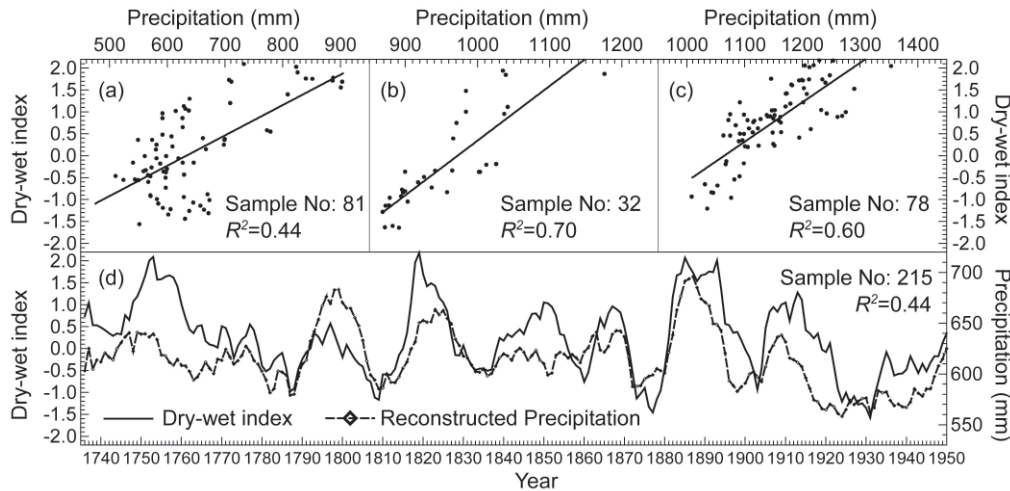


Fig. 4. Comparison of dry-wet index and precipitation data. (a) Dry-wet index in the North China Plain versus instrumental precipitation in Beijing in 1870 ~ 1950; (b) Dry-wet index in the Jiang-Huai area versus instrumental precipitation in Nanjing in 1905 ~ 1936; (c) Dry-wet index in the Jiang-Nan area versus instrumental precipitation in Shanghai in 1873 ~ 1950; (d) Dry-wet index series in the North China Plain versus reconstructed precipitation series over the middle and lower reaches of the Yellow River in 1736 ~ 1950.

#### 4. LOW FREQUENCY PRECIPITATION CHANGE AND EXTREME EVENTS

##### 4.1 Low Frequency Precipitation Change and Regional Differences

To present low-frequency precipitation changes, a 30-year Fast Fourier Transform (FFT) filter is used for smoothing the detrended dry-wet index series. The multi-decadal to centennial dry-wet phases for the whole of eastern China and the 3 sub-regions are listed in Table 1. The characteristics of the precipitation change for the whole of eastern China during 500 - 2000 can be highlighted as follows:

In the period 500s - 870s it is relatively dry with some dry/wet oscillation on a scale of several decades. In the period 880s - 990s it is relatively wet. It turns dry in the period



1000s - 1230s with a couple of short-scale fluctuations. In the period 1240s - 1420s the climate turns wet again, except for a short dry period in 1340s - 1360s. In 1430s - 1530s, it's dry again. Although the most severe drought in the last 1500 years happened around 1640, the climate in the period 1540s - 1910s was still wet. Since the 1920s, the climate turns to dry except for a relatively wet period from the late 1940s to the 1970s. In the period 500s - 1500s the 3 driest 100-year periods in eastern China are 1120s - 1210s, 1430s - 1520s and 670s - 710s and the 3 wettest 100-year periods are 1820s - 1910s 1700s - 1790s and 1330s - 1420s. The general comparison shows that the dry-wet variation identified in our study is consistent roughly with those identified by Gong and Hameed (1991).

Table 1. Multi-decadal to centennial dry-wet periods for the whole of eastern China and the 3 sub-regions during 500 - 2000.

Region	Whole eastern China		North China Plain		Jiang-Huai Area		Jiang-Nan Area	
	Wet Period	Dry Period	Wet Period	Dry Period	Wet Period	Dry Period	Wet Period	Dry Period
Duration	-520s	530s-570s	-510s	520s-580s	-520s	530s-570s	-530s	540s-570s
	580s-630s	640s-700s	590s-620s	630s-700s	580s-640s	650s-700s	580s-840s	850s-940s
	710s-740s	750s-800s	710s-750s	760s-870s	710s-750s	760s-880s	950s-980s	990s-1020s
	810s-830s	840s-870s	880s-1000s	1010s-1280s	890s-1010s	1020s-1220s	1030s-1060s	1070s-1200s
	880s-990s	1000s-1230s	1290s-1330s	1340s-1370s	1230s-1330s	1340s-1370s	1210s-1420s	1430s-1460s
	1240s-1330s	1340s-1360s	1380s-1410s	1420s-1520s	1380s-1460s	1470s-1530s	1470s-1500s	1510s-1540s
	1370s-1420s	1430s-1530s	1530s-1560s	1570s-1640s	1540s-1610s	1620s-1640s	1550s-1630s	1640s-1690s
	1540s-1610s	1620s-1640s	1650s-1910s	1920s-1940s	1650s-1900s	1910s-1940s	1700s-	
	1650s-1910s	1920s-1930s	1950s-1960s	1970s-	1950s-			
	1940s-1970s	1980s-						
First 3 most dry 100-year and anomaly	1120s-1210s 1430s-1520s 620s-710s	(-0.91) <sup>a)</sup> (-0.69) (-0.53)	1130s-1220s 1430s-1520s 620s-710s	(-0.81) (-0.63) (-0.41)	1120s-1210s 1010s-1100s 1440s-1530s	(-0.88) (-0.57) (-0.49)	1090s-1180s 860s-950s 1430s-1520s	(-0.74) (-0.65) (-0.54)
First 3 most wet 100-year and anomaly	1820s-1910s 1700s-1790s 1330s-1420s	(0.73) (0.72) (0.59)	890s-980s 1330s-1420s 1820s-1910s	(0.57) (0.57) (0.55)	880s-970s 1660s-1750s 560s-650s	(0.64) (0.62) (0.51)	1790s-1880s 1240s-1330s 1550s-1640s	(0.78) (0.62) (0.48)

<sup>a)</sup> All values in brackets are anomalies in terms of the standard deviation relative to the mean of the series.

However, certain differences still existed among the 3 sub-regions for low-frequency precipitation change. The FFT filter signals for a 200-year low pass (Fig. 3e) show that in the North China Plain it is relatively dry in 500s - 870s, 1010s - 1280s, 1420s - 1640s and wet in 880s - 1000s, 1290s - 1410s, 1650s - 1960s and then it turns dry again since 1970s. In the Jiang-Huai area, it is relatively wet in 500s - 750s, 890s - 1010s, 1230s - 1460s, 1540s - 1900s and dry in 760s - 880s, 1020s - 1220s, 1470s - 1530s as well as since 1910s. In the Jiang-Nan area, it is dry in 850s - 1200s, 1430s-1540s and wet in 500s - 840s, 1210s - 1420s as well as since 1550s. Although it is still in a wet period, the climate has been turning to dry since the 1880s. The comparison shows that there is a high coherence between these 3 regional dry-wet

variations and those identified by Zhang et al. 1997 (Jiang and Zhang 1997; Zhang 2005) from six regional dry-wet grade series in the North China Plain and lower-Yangtze region. In which, the dry-wet variation in the North China Plain is very close to the low-frequency changes of the dry-wet grade series in Region 1 (most of Hebei Province, Beijing, and Tianjing), 2 (Shanxi Province), 3 (the lower part of Yellow River and Shandong Province) and 4 (Henan Province) in their studies. The dry-wet variation in the Jiang-Huai area and Jiang-Nan area are very similar to those of dry-wet grade series in Region 5 (the downs of the Yangtze River and the basin of the Huai River) and Region 6 (Zhejiang Province, southern Jiangsu Province and Shanghai) in their studies, respectively.

The filter signals for a 100 - 200 year band pass (Fig. 3f) and a 50 - 100 year band pass (Fig. 3g) show that the trends of the changes in the 3 sub-regions are not synchronous during most of the period. In particular there is a contrary change trend between the Jiang-Nan area and the Jiang-Huai area during the 11 - 13th centuries and the 18 - 20th centuries. The contrary change trend between the North China Plain and the Jiang-Nan area has continued to exist since the 16th century. Although the precipitation change in the whole eastern China is mainly driven by the East Asian summer monsoon, this result still indicated that there were different change trends among the 3 sub-regions, particularly on the 50 ~ 200 year time-scale.

#### 4.2 Extreme Events

Extreme events here are defined as periods with widespread (at least over one sub-region), persistent (more than 3 years) and great precipitation anomaly. To identify these events, we selected the periods with a precipitation anomaly of at least 1.645 times the standard deviation higher or lower than the mean value based on the detrended dry-wet index series, meaning that the probability of drought and flood occurrence is 5% respectively, i.e., the total probability of all extreme events occurrence as low as 10%, as suggested by IPCC (2001). Then we used the original drought/flood grade to determine the accurate starting and ending year of each event because of the 10-year time resolution of the detrended dry-wet series. The results are plotted in Fig. 5. It shows that 16 severe, persistent drought events and 18 severe, persistent flood events occurred over eastern China during 501 - 2000. The drought event in 1634 - 1644 (i.e., at the end of the Ming Dynasty) is the most severe sustained drought for eastern China, particularly for the North China Plain and Jiang-Huai area, even extending to the Jiang-Nan area. While the most extreme persistent flooding occurred in 1422 - 1425, which persisted for only 4 years, but covered most of eastern China, and resulted in the government of the Ming Dynasty consecutively relieving agricultural duty for 4 years in numerous provinces (cited from "*the chronological record of events for Emperor Yongle and Emperor Hongxi, History of Ming Dynasty*", compiled by Zhang Ting-Yu in 1739). Meanwhile, persistent flooding in 1056 - 1062 is one of the longest extreme flood periods, triggering a change in the path of the Yellow River in 1060 (He 1991).

A noticeable aspect is that since the middle of the 17th century there were no exceptional, persistent droughts, but several severe, persistent floods over eastern China. The three most severe drought events for the last 300 years occurred mainly in the North China Plain and the Jiang-Huai area, 1927 - 1930 (Liang et al. 2003), 1875 - 1878 (Man 2000b and Ho 1980) and

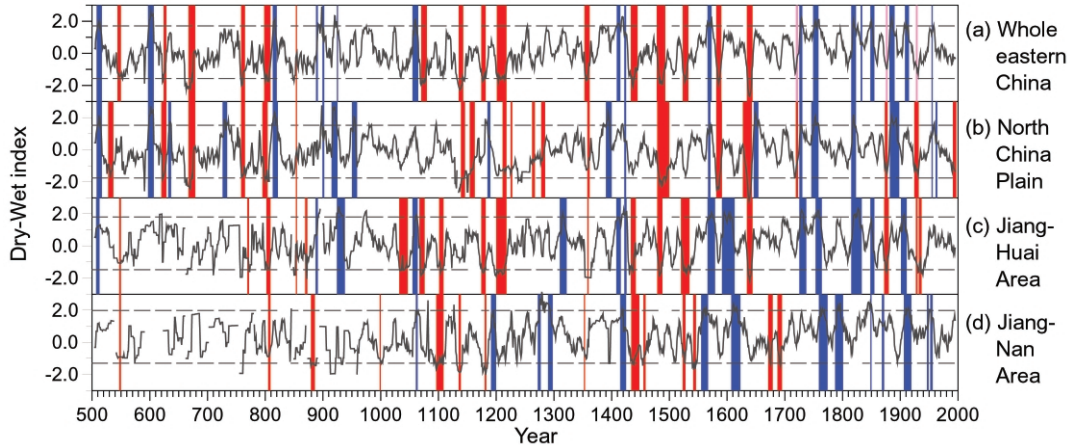


Fig. 5. The severe persistent drought (red bar) and flood (blue bar) events for eastern China and its sub-regions during 501 - 2000; (a) Whole eastern China; (b) North China Plain; (c) Jiang-Huai area; (d) Jiang-Nan area. Gray solid line: dry-wet index series. Gray dash line: the value of the 1.645 times standard deviation higher or lower than mean of series. Pink bar: three most severe, persistent drought events for the last 300 years.

1719 - 1723. These are relatively minor when compared with preceding events. Also, during the 12th ~ 14th centuries there were no severe, persistent floods, but several severe, persistent droughts. However, severe persistent flood events over eastern China became more frequent from the 18th century onwards, occurring twice in the 20th century. The duration and severity of persistent flooding for the period 1908 - 1915 is comparable with that of any extreme persistent flooding prior to the 20th century. The severity of extreme persistent floods in 1908 - 1915 and 1954 - 1956 is also close to that of any events occurring prior to the 20th century.

Finally, we discuss precipitation variability in the 20th century within the context of the last 1500 years. The mean (0.23) and standard deviation (0.80), shown in Table 2 for eastern China during the last hundred years, indicate that the period is relatively wet with smaller variability. Although the variability was also small in the individual sub-regions, different means existed. In the North China Plain, the 20th century had similar dry/wet conditions comparable to the past, but the Jiang-Huai area was relatively dry and the Jiang-Nan area relatively wet. These results thus indicate that precipitation variability during the 20th century cannot

Table 2. Comparison of the mean and standard deviation of the dry-wet series between the 20th century and the whole 1500 years.

	Whole eastern China	North China Plain	Jiang-Huai Area	Jiang-Nan Area
Mean of the whole series	0.06	-0.13	0.16	0.35
Mean of the 20th century	0.23	-0.10	-0.04	0.75
Standard deviation of the whole series	1.00	1.00	1.00	1.00
Standard deviation of the 20th century	0.80	0.78	0.86	0.78

fully represent the range of precipitation variation over the past 2 millennia on a local or regional scale, which was found in many other areas of the world (Woodhouse et al. 1998).

Yet, although the severity and duration of the most severe, persistent drought for the whole of eastern China in the 20th century is dwarfed by that of the last 1500 years, the severity and duration of the most severe, persistent flooding in the 20th century is comparable to that of the last 1500 years.

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