Extreme droughts/floods and their impacts on harvest derived from historical documents in Eastern China during 801–1910

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Abstract. In China, historical documents record a large quantity of information related to climate change and grain harvest. This information can help to explore the impacts of extreme drought or flood on crop production, which can provide implications for the adaptation of agriculture to higher extreme climate probability in the context of global warming. In this paper, reconstructed extreme drought/flood chronologies and reconstructed grain harvest series derived from historical documents were adopted, in order to investigate the connection between the occurrence of extreme drought/flood in eastern China and poor harvest during 801–1910. The results show that more extreme droughts occurred in 801–870, 1031–1230, 1481–1530 and 1581–1650 over whole of eastern China. On regional scale, more extreme droughts occurred in 1031–1100, 1441–1490, 1601–1650 and 1831–1880 in North China, 801–870, 1031–1120, 1161–1220 and 1471–1530 in Jianghuai, 991–1040, 1091–1150, 1171–1230, 1411–1470 and 1481–1530 in Jiangnan. The grain harvest was poor in 801–940, 1251–1650 and 1841–1910, but bumper 951–1250 and 1651–1840, approximately. During the entire period from 801–1910, the greater occurrence of extreme drought in any sub-region of eastern China significantly reduced harvests in the long-term average. The connection between harvest and extreme flood appears to be much weaker, while the co-occurrence of extreme drought and extreme flood in different sub-regions in the same year had a greater impact on harvest yield. The connection between the occurrence of poor harvest and regional extreme drought was weak during the warm epoch of 920–1300 but strong during the cold epoch of 1310–1880, which implies that, historically, a warm climate may have weakened the impact of extreme drought on poor harvests.

1 Introduction

Extreme drought is the most damaging climate-related hazard to agriculture, as it leads to crop failure due to a reduction in water supply. Numerous studies, based on observation data, show that many regions of the world (in particular southern Europe and West Africa) have been experiencing trends toward longer and more intense droughts since the 1950s (IPCC, 2012; Dai, 2011; 2013). The climate in eastern China is dominated by the Asian monsoon, with large precipitation variability, leading to drought and flood at regional, and occasionally larger, scale (Ding et al., 2013). Data show that severe and extreme droughts have become more frequent in Northeast China, North China and the eastern part of Northwest China since the late 1990s, and in Southwest China between 2006–2013 (Zou et al., 2005; 2010; Zhai et al., 2010; Yu et al., 2014). Assessment reports show that droughts affected, on average, 20.9×10^{4} km^{2} of cropland annually from 1949 to 2013, accounting for one sixth of China's total arable land. From 1991 to 2013, the loss of grain crop yields as a result of drought was, on average, 26.75×10^{9} kg per year. From 2004 to 2013, direct economic losses caused by drought averaged CNY ¥63.67 billion (approximately US$10 billion) annually. In addition, projections suggest that the risk of extreme droughts will increase in most of China along with future global warming (Qin et al., 2015).

Recently, a number of studies have focused on the long term droughts events reconstruction and extreme droughts identification through the use of high-resolution proxy data, such as historical documents and tree rings, at local, regional, and national scales. These studies have found that historical extreme droughts had tremendous impacts on agriculture, livelihoods, and socio-economic systems (e.g., Hao et al., 2010a, b; Shen et al., 2007; 2008; Zhang, 2000; 2005; Zheng et al., 2006, 2014a; Gou et al., 2015a, b; Deng et al., 2016; Liu et al., 2017; Yang et al., 2014; Li et al., 2018; Xiao et al., 2017; Zhang et al., 2011; Liang et al., 2006). For example, using Chinese historical documents, Hao et al. (2010b) found that droughts in 1876 and 1877 led to 45% and 50% harvest reduction in each of those years, respectively, caused the price of rice to increase by 5–10 times its normal value, and resulted in the deaths of more than 13 million people, due to famine and plague. Zheng et al. (2014a) found that the severe droughts in 1627–1643 triggered and also significantly promoted widespread peasant uprising, which finally resulted in the collapse of the Ming dynasty.

Meanwhile, several studies also focused on the correlation between climate and grain harvest fluctuations over the past 2000 years at macro-scale. For example, Su et al. (2014) investigated the fluctuations of climate change and grain harvests in China from 206 BCE to 960 CE, and found a high positive correlation between temperature and grain yield. Bumper harvest decades corresponded to warm-normal or warm-wet climate conditions, while poor harvest decades occurred in the context of cold and dry climate conditions. Yin et al. (2015, 2016) further demonstrated that poor harvests between 210 BCE and 1910 CE mostly coincided with cold conditions, when the climate changed from warm to cold along with dry or from wet to dry, and that grain harvests increased during the warm phase. However, these studies did not specifically explore the impacts of extreme droughts on harvests, thus obscuring understanding of the different effects on agriculture induced by short-term extreme events and long-term climate change. Compared with the effects of long-term temperature variation, the impacts of short-term extreme events on agriculture may be more remarkable. Therefore, the study presented here seeks to further investigate the harvest impacts of extreme drought and flood in eastern China from 801 to 1910, using reconstructions of regional grain harvest grades and extreme drought/flood events derived from Chinese historical documents. The aim of the study is to, first, identify the relationship between poor harvests and extreme drought/flood for the whole study period and, then, explore how cold and warm periods, such as the Medieval Climate Anomaly (MCA, 950–1250) and the Little Ice Age (LIA, 1450–1850) (IPCC, 2013), contributed to differences in that relationship.

2 Data and Method

2.1 Data

Two datasets were used, including a chronology of regional extreme drought and flood, and a series of grain harvest grades. Both of them were derived from Chinese historical documents.

(1) The chronology of regional extreme drought and flood. This chronology was reconstructed based on the annual drought/flood grade at 63-stations in eastern China since 137 BCE (east of 105 °E; 25 °N–40 °N approximately). This area was divided into three sub-regions of North China Plain, Jianghuai and Jiangnan (Fig. 1) (Hao et al., 2010a, and renewed by Zheng et al., 2014b). Records for the reconstruction of annual drought/flood grade at 63-stations were extracted from such historical documents as *Twenty-Four Histories* and *Qing History Draft* (official histories of each Chinese dynasties), chronicles, miscellaneous historical books, local gazettes and others. For example, in both *The Book of Tang* and the *New Book of Tang* (two of *Twenty-Four Histories*), the documents at the 19th year of emperor Zhenyuan in Tang Dynasty (803 CE) record: "In day 25 of the 6th month (of the Chinese lunar calendar, or July 17, 803 in the solar calendar; same hereinafter), no rain fell in the Guanzhong area (now Xi'an and surrounding areas) from the 1st month (January 27 to February 24) until now. Hundreds of officials and many people are praying for rain. In day 26 of the 7th month (August 18), rain. In day 17 of the 8th month (September 6), heavy rain. From mid-autumn, drought occurred again". Descriptions such as these clearly provide information about the duration, spatial coverage and intensity of drought. The drought of that year was also recorded in *The Corpus of Huangpu Chizheng* (written by Huangpu Chizheng, 777–835) and in *The Complete Prose Works of the Tang Dynasty* (edited by Dong Gao, 1740–1818). These texts provide different sources for cross-validation, thus, increasing the reliability of the records. Fig. 2 shows a copy of a local gazette, which regularly recorded anomalous climate information at the county, prefectural or provincial level. From this sample, the duration and intensity of drought or flood occurred in Yangzhou Prefecture. For example, in 1848, there were three instances of heavy rain, causing flooding from the 6th to the 8th month. In 1856, severe drought from the 5th to the 8th month led to the Grand Canal drying up (see Figure 2 caption). As this sample suggests, historical documents were usually focused on the events due to no or less precipitation than usual and, thus could be regarded as meteorological drought rather than hydrological or agricultural droughts, although some records also report impacts on the hydrosphere (e.g., rivers drying up for river) or on agriculture (e.g. wilting for crops). Historical documents, therefore, appear to report all droughts equally, rather than only those affecting crops. Similarly, floods recorded in the historical documents could be regarded as more rain or heavier rain than usual, rather than in the context of rivers bursting their banks or tsunamis, although some records also report the impacts of overflowing or bursting lakes and rivers due to more or heavier precipitation.

Based on these records, Zhang (1996) reconstructed a dataset of annual drought/flood grades at 63 stations from 137 BCE. Each station consisted of a local area of approximately 20 counties with the same climate. Grades were classified using ideal frequency criteria of 10% (grade 1, severe drought), 20% (grade 2, drought), 40% (grade 3, normal), 20% (grade 4, flood), and 10% (grade 5, heavy flood) for the whole area and all time. These grades were calibrated based on descriptions of duration, intensity, and area of the drought/flood event during the wet season (usually May to September), and its impact (Table S1). Thus, the season of the drought/flood grade data overlaps with critical agricultural activities and phases of crop growth. The drought/flood grade data are unevenly spatially distributed across the 2000-year period. For example, drought/flood grade data for south China (south of 30 °N approximately) were limited for the period before CE 760, and there were even fewer data for south of the Huaihe River (approximately 34 °N) before CE 300 (Zhang, 1996). However, the coverage of this dataset has extended to south China since 760 CE and, therefore, covered the whole study area. There also existed missing data before 1470, as fewer historical documents have survived from these earlier times (Zhang, 1996; Hao et al, 2016). Statistics show that the mean percentage of available data was 44.1% for 800–1469 and only 20% or lower for periods around 850 and for the 880s–920s, 1230s–1250s, 1360s and 1390s. During the period of 800–1469, the mean percentage of available data reporting "disasters or extremes" (i.e., grade 1, 2, 4, 5) was 41.8% and reporting "normal" (i.e., grade 3) was 2.3% (Fig. S1). Moreover, there was a period of 520 years when no "normal" record existed. This means that most of the available grade data recorded disasters and extremes following the principle of “recording the unusual rather than the normal” in the compilation of Chinese history. In consideration of ideal frequency criteria, in which 40% of all records were defined as "normal" and 60% defined as "disasters and extremes," it could be implied that approximately 70% of the "disasters and extremes" that actually happened in that period were recorded (41.8% in records compared with 60% in the ideal frequency criteria for the whole area and all time). Compared with other datasets, this dataset has certain spatio-temporal advantages. For example, it spans a longer period than the dataset for yearly dryness/wetness grades (1=very wet, 2=wet, 3=normal, 4=dry, 5=very dry) for 120 stations across China from 1470 to 1979 (Academy of Meteorological Science of China Central Meteorological Administration, 1981). In addition, this dataset also covers more areas with higher spatial resolution for local stations (each consisting of around 20 counties), compared with Zhang et al.’s (1997) series of regional dry/wet grades in six areas (consisted of more than 100 counties) from the Lower Yangtze Valley to the North China Plain during 960–1992. Therefore, this dataset provides a valuable proxy and has already been used to study characteristics of precipitation change in eastern China over the past 2000 years. For example, Zheng et al. (2006) used this dataset to reconstruct a 1500 year regional dry/wet index series for the North China Plain (approximately 34–40 °N), the Jiang-Huai area (approximately 31–34 °N) and the Jiang-Nan area (approximately 25–31 °N). Hao et al. (2016) used the dataset to investigate spatial precipitation anomaly patterns in eastern China during centennial cold and warm periods over the past 2000 years.

Since there existed missing from each of the sub-regions (i.e., North China Plain, Jianghuai and Jiangnan) shown in Fig. 1, extreme drought and flood years were identified according to both the coherence of drought/flood grade for each individual station, and the percentage of each drought/flood grade occurrence within the available data in each sub-region. In detail, an extreme drought (or flood) year in any sub-region was defined with two terms: (1) grade 3 occurred in less than 25% of all stations, i.e., disasters or extremes were reported for more than 75% of all stations with available data; and (2) grade 1 and grade 2 (or grade 5 and grade 4) occurred in more than 80% stations with records of disasters or extreme conditions (i.e., stations with grade 3 or missing data were excluded), and grade 1 (or grade 5) occurred in two or more stations. Extreme drought or extreme flood years were defined in this way, as the probabilities for omitting drought and flood records were random and unbiased, despite the greater frequency of missing data in the older records. In other words, if one period had a large number of documents, it was expected to be rich in both drought and flood records, and vice versa. Therefore, the amount of missing data should not have a significant effect on the relative drought-to-flood ratio within the available data. To verify the rationality of this method and criteria, validation was conducted in Hao et al. (2010a), based on 10 extreme events identified from a series of precipitation observations in each sub-region according to a threshold of probabilities of 10% and 90% occurrence. In this validation, all or part of grade 3 stations were deliberately omitted, and only 40% or 60% of stations with disaster or extreme grade were reserved without changing the drought-to-flood ratio within the available data. The results show that, with one exception, years of extreme drought and extreme flood, identified according to this method and criteria, closely matched those extreme events identified by precipitation data, demonstrating that the method and criteria were reasonable. The reason for the close match is that precipitation variability in eastern China is dominated by the East Asian Summer Monsoon (EASM). Therefore, when extreme drought or flood events occur, the precipitation variation for stations within each sub-region usually share similar relative magnitudes. Moreover, this validation also demonstrates that the criteria used for identifying historical sub-regional extreme drought or flood years is equivalent to the definition of extreme climate event with occurrence probability of less than 10% from 1951 to 2000, which was suggested by IPCC (2012) and has often been adopted in other research focusing on extreme climate.

Furthermore, extreme drought or flood years for the whole of eastern China were defined by extreme drought or flood years from the three sub-regions combined, and from the dry-wet index series over the whole of eastern China reconstructed and renewed by Zheng et al. (2006, 2014c), which synthesized annual drought/flood grades from all 63 stations. The criteria to define an extreme drought or flood year for the whole eastern China were: extreme drought (or flood) in all three sub-regions; or extreme drought (or flood) in two sub-regions and no extreme flood (or drought) in the other sub-region; or extreme drought (or flood) in only one sub-region with an annual dry-wet index for the whole of eastern China lower (or greater) than the mean of that series by at least 1.282 times the standard deviation (i.e., less than 10% probability of drought or flood occurrence over the last 2000 years). Moreover, if both extreme drought and extreme flood occurred in different sub-regions in the same year, that year was defined as an extreme year with the co-occurrence of both conditions. In addition, to illustrate the uncertainty of regional extreme drought/flood reconstructions, the confidence levels of these reconstructions were also assessed, based on the percentage of years with data available at 50 year intervals, in which extremely high confidence is defined as more than 99%; very high confidence: >90%; high confidence: >80%; medium confidence: >50%; and low confidence: >33.3%.

(2) Grain harvest grade series. This series was reconstructed based on historical records collected from the *Twenty-Four Histories* and *Qing History Draft*, which included descriptions of yearly grain yield estimates (e.g., a golden bumper year, abundant, plentiful, not bad, slightly poor, poor, very poor, etc.) and related information regarding national food security (e.g., enough, insufficient, starving, famine, beggars everywhere, etc.), features of tax remission induced by agricultural disasters, people’s livelihoods, grain prices and grain storage status at the country scale from 206 BCE to 1910 CE (Su et al,

2014; Yin et al, 2015). In Chinese historical documents, the yearly harvest was usually recorded as a relative level compared to an expected maximum yield, rather than crop yield per hectare, although some records also report impacts of harvest fluctuation on food availability, tax remissions, livelihoods, and so on. Therefore these harvest records exclude differences in absolute yield between sub-regions with different climates, soil fertility and types, crop varieties, etc., as well as difference between historical periods with changing agricultural centres, farming technologies, staple crops, and so on. (Su et al., 2014). As argued by Marks (1998), although it is unclear how yearly harvest percentages in historical times were estimated and what the referee of harvest yield was, also the ratings were probably impressionistic; these harvest rating estimates in Chinese history were commonly used for food supply management and the state granary system administration by officials, and also served as public information for tenants who use the ratings to reduce the amount of rent they were expected to pay landlords. Therefore, it is believed that the harvest rating descriptions recorded throughout Chinese history are a good indication of fluctuations in yearly grain yields (Marks, 1998).

In the dataset, yearly harvest levels were classified into 6 grades: 1-Very poor, 2-Poor, 3-Slightly poor, 4-Average, 5-Near bumper, 6-Bumper. The criteria and methods for year-by-year grading of the documentary records (i.e., grain yield descriptions and related information) were presented by Su et al. (2014) and summarized by Yin et al. (2015). The classification of the yearly harvest grade and descriptions recorded in historical documents is shown in Table S2. Comparison and validation in their research (Su et al., 2014; Yin et al., 2015) shows that this grade system corresponds to a percentage harvest rating system defined by the government as a code in *The Collected Statutes of the Qing Dynasty* (the "*Da-Qing Hui-Dian*" in Chinese, were finally compiled in 1899, and the definition of the harvest rating system is recorded in Vol. 21), in which "Very poor" corresponds to "below 40%" of harvest yield, "Poor" corresponds to 40–50%, "Slightly Poor" corresponds to 50–60%, "Average" corresponds to 60–70%, "Near bumper" corresponds to 70–80%, and "Bumper" corresponds to above 80%.

It is worth noting that the farther back in time, the more records are missing. This is especially the case prior to 760 CE, with regard to both the dataset of annual drought/flood grades for regional extreme drought/flood chronology and the grain harvest grade series. Thus, the study period chosen for investigating the impacts of extreme drought and flood on harvests in eastern China was 801 to 1910. During this study period, several social factors existed which could have influenced China’s total yield, such as changing borders of empires, the expansion of agricultural area (e.g., uplands in the south and southwest colonized by Han settlers during the late Ming and Qing periods), the updated crop varieties introduced from the New World (e.g., peanuts and sweet potatoes), advanced agricultural management technology, and so on. However, such social factors should have only limited influence on yearly harvest grade dataset, since the harvest in the documents was reported as a relative level rather than the absolute yield, also the main grain product area, the staple crop, and the cropping system have been relatively stable throughout the study period (Yin et al., 2015).

In addition, a 2000-year temperature series, with decadal resolution for the whole of China (Ge et al., 2013), was also adopted to identify long-term cold and warm period fluctuations. This temperature series was reconstructed based on 28 temperature proxies using principal component (PC) regression and partial least squares (PLS) regression, respectively (Ge et al., 2013). The comparison showed that the pattern of long-term temperature change over China is roughly consistent with that shown by the IPCC (2013) for the Northern Hemisphere as an overlap of multi-reconstructions since 850.

2.2 Method

Four kinds of data processing method were used in this study, including the moving average, the Wilcoxon rank sum test, the two-sampled t-test and the contingency table with the Chi-square test (χ^2).

(1) To illustrate variations in the occurrence of regional extreme drought and flood from 801 to 1910, the moving-window frequency of extreme drought/flood years in three sub-regions and in the whole of eastern China were first calculated with windows of 50 years and steps of 10 years. For example, a smoothed series was made up of means of 801–850, 811–860, 821–970, and so on. Next, the Wilcoxon rank sum test was applied, to examine which interval had significantly more or fewer drought/flood years compared to all the other intervals. By labelling extreme drought (or flood) years as 1 and non-extreme years as 0, the chronology of extreme drought and flood years could be transformed into a rank series, with the mean of this rank series equivalent to the frequency of drought (or flood) years. Therefore, those intervals with significantly more or fewer drought (or flood) years could be recognized through a Wilcoxon rank sum test performed on the rank series.

(2) To examine whether the occurrence of extreme drought/flood in each sub-region and in the whole of eastern China were connected to poor harvest, harvest grade data for 801–1910 were divided into three categories: extreme drought years, extreme flood years, and non-extreme years, according to the chronology of regional extreme drought and flood for each sub-region or for the whole of eastern China. The two-sampled t-test was then applied to examine whether the means of harvest grade in extreme drought (or flood) years and non-extreme years showed a significant difference. Meanwhile, a contingency table and Chi-square test (χ^2) were adopted to examine the effects of regional extreme drought/flood on each grade of harvest. For example, corresponding to the 720 years with available harvest grade data, there were 97 extreme drought years, 82 extreme flood years, and 541 non-extreme years in the North China Plain. To examine whether there was a significantly greater occurrence of poor harvest (grade 2) in extreme drought years compared to non-extreme years for this sub-region, a contingency table was made by counting extreme drought years with grade 2, extreme drought years with other grades, non-extreme years with grade 2, and non-extreme years with other grades. The chi-square test (χ^2) was then adopted to test the significance.

(3) To illustrate whether there were any differences in the frequency of extreme drought/flood between cold and warm periods, the frequency of extreme drought/flood years was calculated and the Wilcoxon rank sum test was performed for cold and warm periods in the three sub-regions and the whole of eastern China. Similarly, the contingency table and Chi-square test (χ^2) were adopted to examine if there existed significantly different effects of regional extreme drought/flood on harvests during cold and warm periods.

3 Results and Discussion

3.1 The occurrences of regional extreme drought/flood and grain harvest grade during 801–1910

Fig. 3 shows the chronology of extreme drought/flood years and variation for each sub-region (i.e., North China Plain, Jianghuai and Jiangnan area), as well as the whole of eastern China from 801 to 1910. The North China Plain experienced 133 extreme drought years and 113 extreme flood years, Jianghuai had 95 extreme drought and 118 extreme flood years, and Jiangnan 90 extreme drought and 119 extreme flood years (Table 1). The comparison shows that the occurrence of extreme drought was a bit more frequent than extreme flood in the North China Plain due to its sub-humid climate, while both Jianghuai and Jiangnan experienced slightly fewer extreme drought than extreme flood years, due to the humid climate in these regions. The whole of eastern China experienced 126 extreme drought years and 122 extreme flood years, and 20 extreme years when extreme drought and flood co-occurred in different sub-regions.

Moreover, moving-window frequencies of extreme drought/flood years during each 50 years with a decadal step show remarkable multi-decadal variation of both extreme drought and flood occurrences in each sub-region and the whole of eastern China from 801 to 1910 (Fig. 3). In the North China Plain, extreme drought occurred more frequently in 1031–1100, 1441–1490, 1601–1650, 1831–1880, but less in 1151–1200, 1381–1430, 1651–1710, and 1721–1780. Extreme flood occurred more frequently in 941–1000, 1021–1070, 1721–1790, 1801–1830, 1841–1900, but less in 821–880, 1191–1260, and 1461–1550. In Jianghuai, extreme drought occurred more frequently in 801–870, 1031–1120, 1161–1220, 1471–1530, but less in 881–960, 1221–1290, 1301–1350, 1381–1430, 1531–1580, and 1671–1760. Extreme flood occurred more frequently in 1551–1600, 1641–1680, 1691–1710, 1721–1770, 1811–1890, but less in 1261–1310, 1321–1370, and 1461–1550. In Jiangnan, extreme drought occurred more frequently in 991–1040, 1091–1150, 1171–1230, 1411–1470 and 1481–1530, but less in 1231–1320, 1361–1420, 1691–1750 and 1841–1890. Extreme flood occurred more frequently in 991–1040, 1151–1230, 1241–1300, 1400–1430 and 1821–1880, but less in 851–970 and 1300–1370. For the whole of eastern China, extreme drought occurred more frequently in 801–870, 1031–1230, 1481–1530 and 1581–1650, but less in 891–1000, 1231–1320, 1381–1430, 1531–1580, 1651–1780, 1791–1850 and 1881–1910. Extreme flood occurred more frequently in 811–840, 951–990, 1051–1070, 1381–1430, 1641–1670, 1721–1770 and 1810–1870, but less in 841–900, 1321–1380, 1431–1560, 1581–1640 and 1671–1700. Moreover, there was significantly more frequent co-occurrence of extreme drought and flood in 1291–1300, 1481–1500 (both with 2 years) and 1581–1600 with 3-years, respectively.

Figure 4a shows the series of grain harvest grades from 801 to 1910, with 390 years (35.1%) of missing data. Percentages for each harvest grade were 4.9% (grade 1), 16.0% (grade 2), 18.4% (grade 3), 14.4% (grade 4), 6.9% (grade 5), and 4.2% (grade 6) (Table 2). In total, the percentage of all poor harvest years (grades 1, 2 and 3) was 39.3%, while the percentage of bumper harvest years (grades 5 and 6) was only 11.2%. Moreover, the moving-window percentage for each harvest grade and data missing for each 50 years with a decadal step (Fig. 4b) show an evident jump around the 1640s, when there was an increase in grade 4 years and a decrease in missing data years. This is mainly because the *Qing History Draft* recorded more "average" harvest years, while the *Twenty-Four Histories* excluded most "average" years, according to the principle of "recording unusual rather than common events", as argued in Yin et al. (2015). Therefore, to avoid the effect of missing data and to maintain the homogeneity in statistics, data missing years and "average (grade 4)" years were excluded in the analysis, as adopted in Zheng et al. (2006). Relative percentages for years with each anomalous harvest grade (i.e., 1, 2, 3, 5, and 6) compared with total anomalous years were calculated for each 50-year moving-window (Fig. 4c) to illustrate variation in grain harvest during 801–1910. By excluding grade 4 and missing data years, the relative percentages for each harvest grade for the whole period were 9.6% (grade 1), 31.8% (grade 2), 36.4% (grade 3), 13.8% (grade 5), and 8.4% (grade 6) (Table 2). Noted that, in Fig. 4c, grades 1 and 2 (hereafter, "grade 1+2") were combined as the poor group, and grades 5 and 6 (hereafter, "grade 5+6") as the bumper group, as grade 1 and grade 6 were only 4.9% and 4.2%, respectively, in all years. For the entire period, the relative percentages of grade 1+2 and grade 5+6 were 41.4% and 22.2%, respectively.

According to the variation of the occurrences of poor and bumper harvest (Fig. 4c), the grain harvest for 801–1910 can be roughly divided into five periods. From 801 to 940, the grain harvest was generally poor with fewer bumper harvests (only 7.1% for grade 5+6) but more slightly poor harvests (51.4% for grade 3). From 951 to 1250, there were more bumper harvests (31.9% for grade 5+6) with relatively fewer poor harvest (37.7% for grade 1+2, 30.4% for grade 3), with the exception of 1121–1170, when the occurrences of harvest grades was similar to that of the 9th Century. From 1251 to 1650, there were noticeably more poor harvests (63.1% for grade 1+2), but very few bumper harvest years (9.2% for grade 5+6). In 1651–1840, there were more bumper harvests (53.5% for grade 5+6) and fewer poor harvests (9.3% for grade 1+2). After 1841, the grain harvest became generally poor again with fewer grade 5+6 (9.1%) but more slightly poor (63.6% for grade 3) harvest grades. On the whole, the harvest was generally better in 951–1250, corresponding to a warmer climate, and lower in 1450–1650, corresponding to a colder climate, as argued in Yin et al. (2015, 2016). However, harvests were again higher in 1651–1840, corresponding to a cold climate. This can also be confirmed by other datasets from independent sources. For example, according to harvest reports in the Archives of the Qing Dynasty, the mean harvest percentage over eastern China for 1730–1820 was even greater than 70% (i.e. near bumper) (Ge and Wang, 1995). In Guangdong Province, southern China, this was over 75% for 1707–1800 (Marks, 1998).

3.2 Effects of regional extreme drought/flood on harvest during 801–1910

Table 3 shows the mean harvest grade for all extreme drought/flood years and non-extreme years for the three sub-regions and the whole of eastern China from 801 to 1910. The mean was 3.3 for all non-extreme years over the whole of eastern China, and similar in the three sub-regions. The two-sampled t-test showed the mean harvest grade for all extreme drought years was significantly lower than that for non-extreme years, which was 2.95 for all extreme drought years in the whole of eastern China, 2.84 for the North China Plain, 2.89 for Jiangnan, and 2.99 for Jianghuai. However, no significant differences were detected for extreme flood years in any sub-region. These results indicate that more occurrence of extreme drought in any part of eastern China could lead to a significantly reduced harvest in the long term average, while more occurrence of extreme flood seemed to have no significant impact on average harvest yield. This is primarily due to the fact that extreme droughts usually cover an immense area dominated by a single large-scale air mass, leading to significant and extensive impacts on agriculture. On the other hand, extreme floods were mostly caused by rainstorms induced by the confrontation of air masses, which usually occur across a relatively narrow belt. Meanwhile, rainstorms could irrigate agricultural land in areas surrounding the extreme floods and, thus, improve grain yields, leading to limited impacts of extreme floods on harvests over an immense area (Zhang, 1982). However, the mean harvest grade in years of co-occurrence of extreme drought and flood for the whole of eastern China was a mere 2.53 (Table 3), which is much lower than the mean of 3.30 for non-extreme years. This implies that the co-occurrence of extreme drought and extreme flood in different sub-regions of eastern China in the same year had a greater impact on harvest yield.

To illustrate the connection between harvest and regional extreme drought/flood, Table 4 shows the frequency of each harvest grade (i.e., the percentage of years with each harvest grade, accounting for all years without missing data) for extreme drought/flood years and non-extreme years at each sub-region and for the whole of eastern China. It was found that the frequency of poor harvest (grade 1+2) for extreme drought years in the North China Plain significantly increased from 29.2% (for non-extreme years, hereinafter) to 47.4%, with frequencies of grade 1 and grade 2 significantly increasing from 6.3% and 22.9% to 13.4% and 34.0%, respectively. Compared with non-extreme years, although extreme drought in Jianghuai did not lead to significant increases in frequency of grade 1 or grade 2, it caused a significant increase in the frequency of grade 1+2 (poor harvest) from 31.5% to 41.9%, and a significant decrease in the frequency of grade 5 (near bumper harvest) from 12.2% to 5.4%. For extreme drought years in Jiangnan, the frequency of grade 1+2 (poor harvest) significantly increased from 30.3% to 51.5%, with the frequency of grade 2 significantly increasing from 22.9% to 42.4% and the frequency of grade 4 ("average" harvest) significantly decreasing from 23.8% to 12.1%. When extreme droughts occurred in the whole of eastern China, it was found that, not only did the frequencies of grade 1 and grade 2 increase from 6.8% and 22.4% to 11.7% and 36.2%, respectively, but also the frequency of grade 4 significantly decreased from 24.6% to 13.8%. Moreover, it was also found that the co-occurrence of extreme drought and flood in the whole of eastern China, though only in certain years, had the greatest impact on harvest, leading to the frequency of grade 2 significantly increasing from 22.4% to 60.0%. In summary, the more frequent occurrence of extreme drought in any sub-region of eastern China could lead to significant increases in the frequency of poor harvests (grade 1+2) when compared with non-extreme years. This relationship may have been caused by both reductions in water supply and other indirect pathways. For example, droughts might harm human and domestic animal health or result in migration, leading to a reduced agricultural labour force. In addition, extreme events might reduce public revenue or increase public expenses, thus increasing political and economic instability, and further affecting agricultural activities (Zheng et al., 2014a).

However, the connection between harvest and extreme flood seems to have been much weaker. No significant difference was found between the frequency of poor harvest in extreme flood years and non-extreme years, although extreme floods could also cause significant decreased bumper harvest frequency in some cases. Extreme floods in Jianghuai and Jiangnan, for instance, both led to significant decreases in the frequency of grade 5 (near bumper) harvests from 12.2% and 11.9% to 5.7% and 5.6%, respectively. It is possible that rainfall in these two humid areas was already sufficient for crop growth, thus, extreme floods had a negative impact on harvest potential (Zheng and Huang, 1998).

3.3 The difference of regional extreme drought effects on grain harvest between warm and cold periods

To explore whether occurrence of regional extreme drought/flood differently effected grain harvests in warm and cold periods, a multi-proxies-based temperature reconstruction with a decadal resolution for all of China is presented in Fig. 3e. It is shown that temperature across China from 801 to 1910 experienced two long-term anomalous epochs, both of which contained several multi-decadal fluctuations. These two anomalous epochs was the warm epoch during 920–1300 and the cold epoch during 1310–1880 (Fig.4), in which the first one covered MCA (950–1250) and the latter covered LIA (1450–1850).

The difference in frequency of extreme drought/flood between the warm (920–1300) and cold (1310–1880) epochs (Table 5) shows only a small difference in frequency of extreme drought between warm and cold epochs for the North China Plain and Jianghuai. However, in Jiangnan, extreme droughts occurred more frequently between 920 and 1300 (10.8%) than between 1310 and 1880 (6.5%). Therefore, extreme drought for the whole of eastern China in 920–1300 (13.9%) was significantly more frequent than in 1310–1880 (9.6%). As for extreme flood frequency, significant differences were only found in the south. Compared with 1310–1880, there were significantly fewer extreme floods in Jianghuai but more in Jiangnan from 920 to 1300. After the composition of their opposite tendency, no significant differences in the frequency of extreme floods between 920–1300 and 1310–1880 were found for the whole of eastern China. Thus, there were slightly more extreme droughts during the warm period than the cold period, while no differences were found in the frequency of extreme floods over eastern China.

As found in section 3.2, more occurrence of extreme drought in eastern China led to a significant increase in the frequency of poor harvests (grade 1+2) when compared with non-extreme years. Since more extreme droughts occurred over eastern China in 920–1300 than in 1310–1880, the harvest in the warm epoch could be expected to be worse than in the cold epoch. However, as Yin et al. (2015, 2016) found, the harvest in warm epoch was better than that in cold epoch. This suggests that the effects of regional extreme drought on the grain harvest differed between warm and cold epochs. Table 6 illustrates this difference, by showing the frequency of poor harvest (grade 1+2) occurrences in extreme drought/flood years and non-extreme years for warm and cold epochs, i.e., 920–1300 and 1310–1880. Noted that there exists a shift in the distribution of each harvest grade after the 1640s due to an increase in grade 4 years and a decrease in missing data years. Meanwhile, there existed an evidently high frequency of bumper harvests (grade 5+6) from the 1650s to the 1810s. Therefore, the connection between poor harvest (grade 1+2) and regional extreme drought for 1650–1880 were also investigated.

The results show that, during the warm epoch of 920–1300, there was no significant connection between the occurrence of poor harvest and regional extreme drought, although the frequency of poor harvest in extreme drought years was slightly higher than in non-extreme years for each sub-region. In contrast, during the cold epoch of 1310–1880, the frequency of poor harvest in extreme drought years was significantly higher than in non-extreme years, which indicates that the connection between the occurrence of poor harvest and extreme drought was still significant. Moreover, similar characteristics were found for the latter half of the cold period from 1650 to 1880, which indicates that the shift of harvest grade distribution did not affect the connection between poor harvest and extreme drought/flood during the cold epoch. These results suggest that the warm period could weaken the impact of extreme drought on poor harvests in historical times. Possible cause might be that, there was low and limited adaptability during that period, and the warm climate provided more thermal resources and extended the growing season, thus increasing the multiple cropping index and providing more thermal-limited lands for growing crops. This gave people more options to adapt to climatic variation, and mitigated the impacts of extreme drought on harvest yield. As assessed by Zhang (1982), the harvest may change by approximately 10% if the temperature changed by 1 ℃ on national scale based on the data from 1909 to 1979, in which the harvest increased significantly in 7 of 8 warm years. However, a cold climate could limit multiple cropping and shrink the area of arable land, leading to the harvest becoming more vulnerable to extreme drought. Moreover, as reported by Zhang et al. (2007), limited resources could also cause social turbulence, such as famine, peasant uprising, the outbreak of war, and population decline, all of which may further increase agricultural vulnerability. Therefore, even though the occurrence of extreme drought was slightly more frequent in the warm period of 920–1300, the frequency of poor harvests did not increase significantly.

3.4 Discussion

Chinese historical documents provide a unique proxy for reconstructions of climate change and annual harvest grades, which enables an examination of the impacts of climate change on grain yields up to thousand years ago. Compared with previous research (e.g., Su et al., 2014; Yin et al., 2015, 2016), which focused on the correlation between temperature variation and grain harvest fluctuations at decadal resolution during historical times, this study presented an examination of the impacts of extreme drought/flood on grain harvests and their differences between warm and cold periods year by year. Therefore, this study helps to improve understanding of the climatic impacts on agriculture induced by short-term extreme events within the context of long-term temperature change. The finding of a non-significant connection between the occurrence of poor harvests and regional extreme drought during a warm climate era may help to provide the implications for agricultural adaptation to future global warming along with higher extreme climate probability.

However, several issues still exist that could lead to uncertainty. First, due to missing records before 1400, the reconstructed chronology of regional extreme drought and flood may not include all events. For example, as shown in Fig. 3, the reconstructed chronologies of regional extreme drought and flood for several periods (e.g., 850–950, 1350–1400 in both Jianghuai and Jiangnan, and 1250–1300 in Jianghuai) had low confidence levels. Moreover, the reconstructed chronologies for 1150–1200 in the North China Plain, 1200–1250 in Jianghuai, and 800–850, 950–1100 in Jiangnan also had medium confidence levels. Therefore, most of the reconstructed chronology of extreme drought and flood for the whole of eastern China before 1400 was only in medium or low confidence. Second, there may also be limitations in the grading of annual harvests for some years. For example, in 1181, the harvest was assessed as grade 6, according to the description, "It is a plentiful year after sufficient rainfall killed locusts" in the *History of Song* (one of the *Twenty-Four Histories*), which usually recorded country-wide events. Thus, this description was regarded as a record at national scale. However, the *Compilation of Essential Regulations of the Song Dynasty* (*Song Hui-Yao Ji-Gao* in Chinese, edited by Xu Song, Vol. 66, Vol. 69), reported widespread "drought" in southern China that year, which led to poor or slightly poor harvests at the sub-regional scale. Similar inconsistencies in the historical records have also been found in 1032, 1073, 1353, and 1638. These cases suggest that the grain harvest descriptions recorded in *Twenty-Four Histories* may not indicate anomalous harvests for all years at the national scale. In addition, around the 1650–60s, there was a clear jump to grade 5+6 (bumper harvest), yet this period is commonly recognized in previous literatures as having poor harvests and famine in this coldest interval of the Little Ice Age. Also, the periods 1130–1150 and 1210–1270 (the early and later Southern Song Dynasty), 880–980 (later Tang Dynasty and Five Kingdoms) and around 1400, have remarkably more missing harvest grade data. These limitations introduce uncertainty by affecting the statistical relationship between harvest and extreme drought/flood in certain periods. Therefore, further research is required, especially in the search for more historical records from the other scattered documents to supplement the evidence recorded in the *Twenty-Four Histories*.

4 Conclusion

Changes in the occurrence of regional extreme drought/flood and grain harvest, and possible connections between the two, were investigated for 801–1910, using a reconstructed chronology of regional extreme drought/flood and a series of grain harvest grades. The results reveal significantly more extreme droughts in 801–870, 1031–1230, 1481–1530 and 1581–1650, and more extreme floods in 811–840, 951–990, 1051–1070, 1381–1430, 1641–1670, 1721–1770 and 1810–1870 over the whole of eastern China. Regionally, more extreme droughts occurred in different intervals, including 1031–1100, 1441–1490, 1601–1650 and 1831–1880 for North China, 801–870, 1031–1120, 1161–1220 and 1471–1530 for Jianghuai, 991–1040, 1091–1150, 1171–1230, 1411–1470 and 1481–1530 for Jiangnan. The grain harvest was generally poor in, approximately, 801–940, 1251–1650 and 1841–1910, but bumper in 951–1250 and 1651–1840. Both t-test and Chi-square test (χ^2) demonstrated that more extreme droughts in any sub-region of eastern China could lead to a significantly higher frequency of poor harvests. The co-occurrence of extreme drought and extreme flood in different sub-regions in the same year could result in a greater impact on harvest yield. However, the occurrence of extreme flood seemed to have no significant impact on harvest yield in the long-term average. Moreover, the comparison showed extreme drought over the whole of eastern China occurred more frequently in the warm epoch of 920–1300 than that in the cold epoch of 1310–1380. However, during the warm epoch, the connection between the occurrence of poor harvest and regional extreme drought was weak, though the frequency of poor harvests in extreme drought years was still slightly higher than in non-extreme years for each sub-region. This is primarily due to the provision of more thermal resources and the extended growing season in the warm climate, which increased the multiple cropping index and created more thermal-limited lands for agricultural crops, allowing for more options to mitigate the impacts of extreme drought on the harvest. Thus, the study provides further historical evidence to help explore the implications for agricultural adaptation to future global warming along with higher extreme climate probability.

Data availability. All data used in the paper are available from the corresponding authors on request.

The Supplement related to this article: Table S1, Table S2 and Fig. S1

Author contribution. JZ, ZH & SL contributed the idea and design the structure of manuscript; JZ & SL collected the data; ZH, MW, JC & XZ analyzed the data; ZH, JZ & MW wrote the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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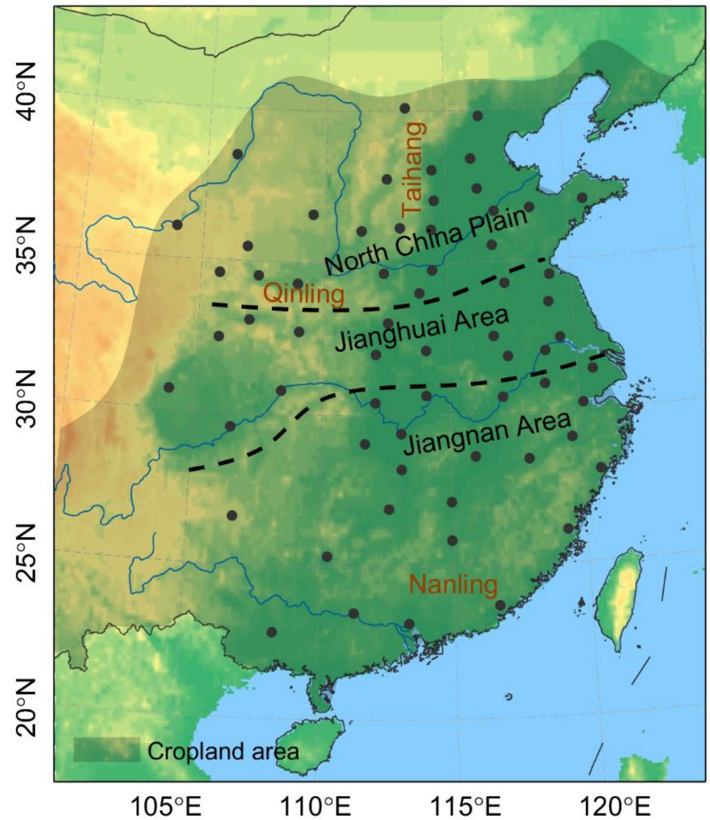
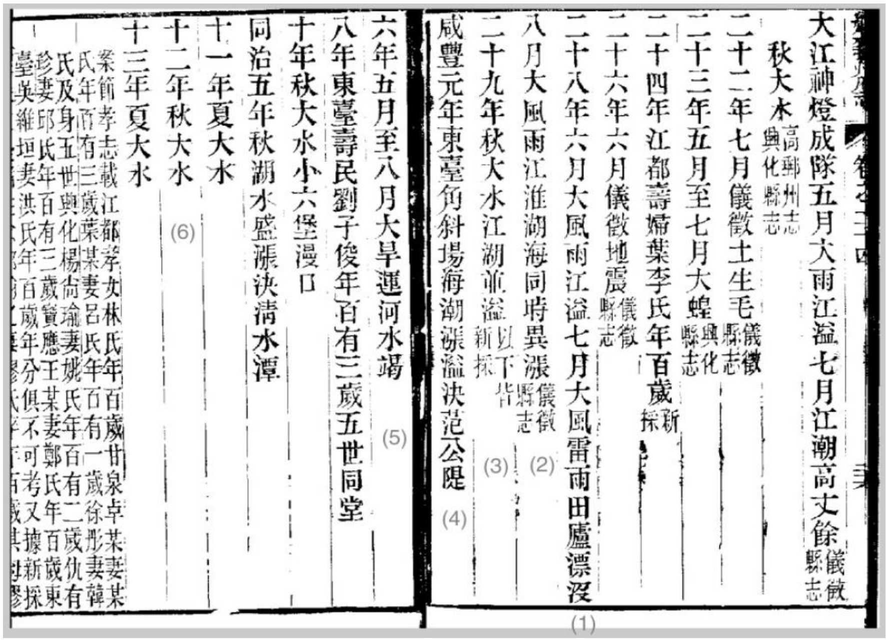


Figure 1: Location of 63 drought/flood grade data stations and sub-region divisions. The shaded area indicates approximate cropland distributed approximately from 801 to 1910.



大江神燈成隊五月大雨江溢七月江潮高丈餘儀徵縣志
秋大水高郵州志興化縣志
二十二年七月儀徵土生毛儀徵縣志
二十三年五月至七月大蝗興化縣志
二十四年江都壽婦葉李氏年百歲新採
二十六年六月儀徵地震儀徵縣志
二十八年六月大風雨江溢七月大風雷雨田廬漂沒
八月大風雨江淮湖海同時異漲儀徵縣志
二十九年秋大水江湖並溢以下皆新採
咸豐元年東臺角斜場海潮漲溢決范公隄
六年五月至八月大旱運河水竭
八年東臺壽民劉子俊年百有三歲五世同堂
十年秋大水小六堡漫口
同治五年秋湖水盛漲決清水潭
十一年夏大水
十二年秋大水
十三年夏大水
案節孝志載江都孝女林氏年百歲甘泉卓某妻某
氏年百有三歲葉某妻呂氏年百有一歲徐彤妻韓
氏及身五世興化楊尚瑜妻姚氏年百有二歲仇有
珍妻邱氏年百有三歲寶應王某妻鄭氏年百歲東
臺吳維垣妻洪氏年百歲年分俱不可考又據新採

Figure 2: An example of anomalous climate information recorded in local gazettes (Quoted from Gazettes of Yangzhou Prefecture, compiled in 1874). The two pages list anomalous climate information in that region from 1842 to 1874, read from right to left, and dated according to the Chinese lunar calendar. Numbers in brackets are added by the authors to show meaning: (1) The 28th year (of Daoguang emperor, 1848), the 6th month, due to the strong wind and heavy rain, the Yangtze River overflowed; the 7th month, because of strong wind and thunder storms, fields and houses were submerged. (2) The 8th month, strong wind and heavy rain, the level of the Yangtze River, the Huaihe River, the (Gaoyou) Lake, and the sea level abnormally rose at the same time, citation from Gazettes of Yizheng County (a county in the prefecture), where records of "strong wind" and "the sea level abnormally rose" also suggested heavy rain induced by a typhoon. (3) There was a flood in the autumn of the 29th year (1849), the Yangtze River and the (Gaoyou) Lake overflowed at the same time. Notes of "Below are newly collected", suggested that these records were quoted from earlier local gazettes. (4) The 1st year of Emperor Xianfeng (1851), Jiaoxiechang (the name of a salt field) of Dongtai County (a county in the prefecture), the tide from the sea overflowed and broke the Sea Wall of Mr. Fan. (5) The 6th year (1856), the 5th to 8th months, there was severe drought and the Grand Canal dried up. (6) Autumn of the 12th year of Emperor Tongzhi (1873), there was a flood.

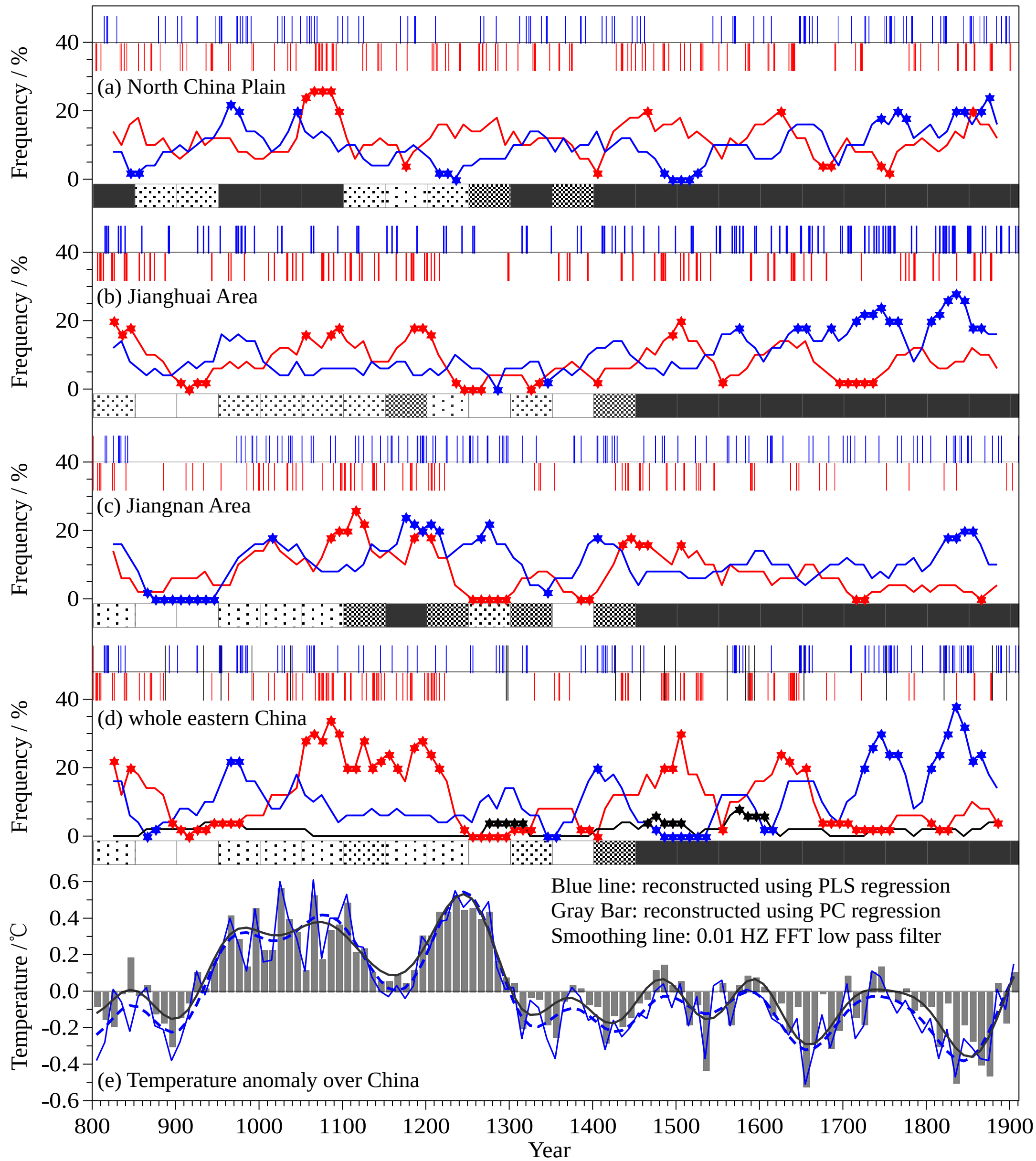


Figure 3: The chronology (vertical line in the top row of each plate) and frequency (star-line, 50-year moving-window with decadal time step) of extreme drought (red) and flood (blue) the North China Plain (a), Jianghuai (b), Jiangnan area (c), and the whole of eastern China (d) from 801 to 1910. Black line in plate (d) indicates the same frequency for the co-occurrence of extreme drought and flood for the whole of eastern China. The stars represent intervals with significantly more or less extreme drought and flood compared with all other intervals, based on the Wilcoxon rank sum test. The bars on the bottom row of each plate illustrate confidence levels (probability in being correct, PBC) for each reconstructions at 50 years intervals: extremely high confidence (PBC>99%): dark; very high confidence (PBC>90%): 50% shaded dark; high confidence (PBC>80%): 25% shaded dark; medium confidence (PBC>50%): 12.5% shaded dark; and low confidence (PBC>33.3%): blank. (e) The temperature series over China (at decadal resolution) for comparison, which was reconstructed based on 28 temperature proxies using principal component (PC) regression and partial least squares (PLS) regression (Ge et al., 2013).

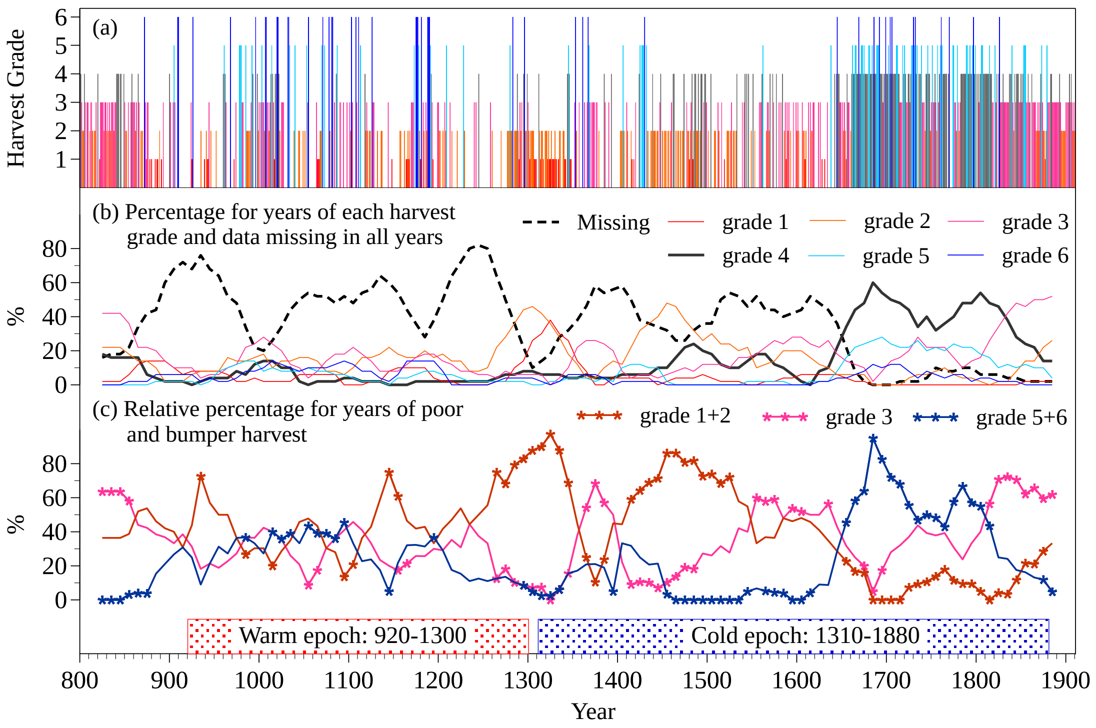


Figure 4: (a) The yearly harvest grade from 801–1910, 1-Very poor (red), 2-Poor (orange), 3-Slightly poor (pink), 4-Average (black), 5-Near bumper (light blue), 6-Bumper (blue). (b) The variation of percentage for the years with each harvest grade and missing data, using a moving-window of 50 years by decadal step. (c) Relative percentage for years of poor (grade 1+2), slightly poor (grade 3) and bumper (grade 5+6) harvest compared with total years, excluding "average" harvest and missing data years, using a moving-window of 50 years by decadal step. Stars: intervals with significantly higher or lower percentage compared with all other intervals, using the Wilcoxon rank sum test. Box: the warm and cold epochs identified from the temperature reconstruction for all of China, shown in Figure 2e.

Table 1: Frequency of extreme drought and flood occurrence in each sub-region and the whole of eastern China, 801–1910.

Sub-region	Extreme event	Number of years	Frequency (%)
North China Plain	Drought	133	12.0
	Flood	113	10.2
Jianghuai area	Drought	95	8.6
	Flood	118	10.6
Jiangnan area	Drought	90	8.1
	Flood	119	10.7
Whole eastern China	Drought	126	11.4
	Flood	122	11.0
	Co-occurrence of Drought and Flood	20	1.8

Table 2: Number of years and percentage for each harvest grade and missing data, 801-1910.

Harvest grade	1	2	3	4	5	6	Data missing
Number of years	54	178	204	160	77	47	390
% in all years	4.9	16.0	18.4	14.4	6.9	4.2	35.1
% in years excluding grade 4 and missing data	9.6	31.8	36.4	-	13.8	8.4	-

Table 3: Comparison between mean harvest grades in extreme drought/flood years and non-extreme years for the three sub-regions and the whole of eastern China.

	Non-extreme	Extreme drought	Extreme Flood	Co-occurrence$^{\#}$
North China Plain	3.31	**2.84*****	3.20	--
Jianghuai Area	3.27	**2.99***	3.23	--
Jiangnan Area	3.28	**2.89****	3.21	--
Whole of eastern China	3.30	**2.95****	3.27	**2.53****

Note: Significance level: ***, $p<0.01$; **, $p<0.05$; *, $p<0.05$. $^{\#}$: The co-occurrence of extreme drought and extreme flood in different sub-regions.

Table 4: Comparison of the frequency of each harvest grade between extreme drought/flood years and non-extreme years, 801–1910.

Region	Harvest grade		1	2	3	4	5	6	1+2[a]	5+6[b]	Total
North China Plain	Non-Extreme	Years	34	124	158	129	57	39	158	96	541
		%	6.3	22.9	29.2	23.8	10.5	7.2	29.2	17.7	
	Extreme drought	Years	13	33	22	17	9	3	46	12	97
		%	**13.4****	**34.0****	22.7	17.5	9.3	3.1	**47.4*****	12.4	
	Extreme flood	Years	7	21	24	14	11	5	28	16	82
		%	8.5	25.6	29.3	17.1	13.4	6.1	34.1	19.5	
Jianghuai Area	Non-Extreme	Years	39	137	153	127	68	34	176	102	558
		%	7.0	24.6	27.4	22.8	12.2	6.1	31.5	18.3	
	Extreme drought	Years	8	23	21	12	4	6	31	10	74
		%	10.8	31.1	28.4	16.2	***5.4****	8.1	**41.9***	13.5	
	Extreme flood	Years	7	18	30	21	5	7	25	12	88
		%	8.0	20.5	34.1	23.9	***5.7****	8.0	28.4	13.6	
Jiangnan Area	Non-Extreme	Years	42	129	158	134	67	34	171	101	564
		%	7.4	22.9	28.0	23.8	11.9	6.0	30.3	17.9	
	Extreme drought	Years	6	28	14	8	5	5	34	10	66
		%	9.1	**42.4*****	21.2	***12.1*****	7.6	7.6	**51.5*****	15.2	
	Extreme flood	Years	6	21	32	18	5	8	27	13	90
		%	6.7	23.3	35.6	20.0	***5.6****	8.9	30.0	14.4	
Whole eastern China	Non-Extreme	Years	35	115	146	126	59	32	150	91	513
		%	6.8	22.4	28.5	24.6	11.5	6.2	29.2	17.7	
	Extreme drought	Years	11	34	21	13	7	8	45	15	94
		%	**11.7***	**36.2*****	22.3	***13.8*****	7.4	8.5	**47.9*****	16.0	
	Extreme flood	Years	7	20	35	19	10	7	27	17	98
		%	7.1	20.4	35.7	19.4	10.2	7.1	27.6	17.3	
	Co-occurrence[#]	Years	1	9	2	2	1	0	10	1	15
		%	6.7	**60.0*****	13.3	13.3	6.7	0.0	**66.7*****	6.7	

Values in bold with stars denote significant more or fewer (also in italic) occurrences, using Chi-test (χ^2) at level of: ***, $p<0.01$; **, $p<0.05$; *, $p<0.1$. [a]: for the occurrences of grade 1 and grade 2 in total. [b]: for the occurrences of grade 5 and grade 6 in total. [#]: for the co-occurrence of extreme drought and extreme flood in different sub-regions.

Table 5: Comparison of frequency of extreme drought/flood between warm and cold epochs.

Sub-Region		Frequency (%) Warm epoch 920–1300	Frequency (%) Cold epoch 1310–1880
North China Plain	extreme drought	12.6	11.7
	extreme flood	9.4	11.2
Jianghuai Area	extreme drought	9.2	7.9
	extreme flood	**7.1*****	**13.3*****
Jiangnan Area	extreme drought	**10.8****	**6.5****
	extreme flood	**13.6***	**9.8***
whole eastern China	extreme drought	**13.9****	**9.6****
	extreme flood	9.7	11.9

Values in bold with stars denote significantly more or fewer (also in italic) frequent extreme droughts/floods in 920–1300 compared with 1310–1880, using rank sum test at level of: ***, p<0.01; **, p<0.05; *, p<0.1.

Table 6: Comparison of frequency of poor harvest (grade 1+2) occurrences for extreme drought years and non-extreme years for warm and cold epochs.

Region	Anomalous temperature epochs		Warm epoch 920–1300		Cold epoch 1310–1880		in which 1650–1880	
	Harvest grade		1+2	others	1+2	others	1+2	others
North China Plain	Non-Extreme	Years	53	90	78	233	6	159
		%	37.1	62.9	25.1	74.9	3.6	96.4
	Extreme drought	Years	13	13	24	31	5	17
		%	50.0	50.0	**43.6*****	56.4	**22.7*****	77.3
Jianghuai Area	Non-Extreme	Years	57	90	86	237	10	154
		%	38.8	61.2	26.6	73.7	6.1	93.9
	Extreme drought	Years	12	12	16	20	4	12
		%	50.0	50.0	**44.4****	55.6	**25.0*****	75.0
Jiangnan Area	Non-Extreme	Years	49	79	86	254	15	173
		%	38.3	61.7	25.3	74.7	8.0	92.0
	Extreme drought	Years	13	14	19	11	1	5
		%	48.2	51.8	**63.3*****	36.7	16.7	83.3
Whole eastern China	Non-Extreme	Years	48	79	76	229	8	156
		%	37.8	62.2	24.9	75.1	4.9	95.4
	Extreme drought	Years	15	20	23	20	3	8
		%	42.9	57.1	**53.5*****	46.5	**27.3****	72.7

Values in bold with stars denote significantly more occurrences, using Chi-test (χ^2) at level of: ***, $p<0.01$; **, $p<0.05$; *, $p<0.1$.