Clim. Past Discuss., https://doi.org/10.5194/cp-2019-14
Manuscript under review for journal Clim. Past
Discussion started: 11 February 2019


# Extreme droughts/floods and their impacts on harvest derived from historical documents in Eastern China during 801–1910

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**Abstract.** Chinese historical documents recorded plenty of information related with climate change and grain harvest, which are helpful to explore the impacts of extreme drought/flood on crops and the implications on adaptation for agriculture to more extreme climate probability in the context of global warming. Here, we used the reconstructed extreme drought/flood chronologies and reconstructed grain harvest series derived from historical documents to investigate the connection between the occurrences of extreme drought/flood in eastern China and poor harvest during 801–1910. The results showed that more extreme droughts occurred in 801–870, 1031–1230, 1481–1530 and 1581–1650 over whole 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 periods of 801–940, 1251–1650 and 1841 to 1910, but bumper in periods of 951–1250 and 1651–1840 approximately. For entire period of 801–1910, more occurrence of extreme drought in any sub–region of eastern China could significantly reduce harvest in the long term average, but the connection between harvest and extreme flood seemed to be much weaker. The co-occurrence of extreme drought and extreme flood in different sub-regions in the same year had a greater impact on harvest yield. However, the connection between the occurrence of poor harvest and regional extreme drought was weak in the warm epoch of 920–1300 but strong in the cold epoch of 1310–1880, which implicated warm climate might weaken the impact of extreme drought on poor harvest during historical times.

## 1 Introduction

Extreme drought is the most damaging climate-related hazard to agriculture, which leads to crop failure through reductions in water supply. Numerous studies from observation data showed many regions (especially in southern Europe and West Africa) of the world have experienced trends toward more intense and longer droughts since the 1950s (IPCC, 2012; Dai, 2011; 2013). The climate in eastern China is dominated by Asian monsoon with large precipitation variability, which usually leads to drought and flood not only at regional scale but also at larger scale occasionally (Ding et al., 2013). The observation showed 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 during 2006–2013 (Zou et al., 2005; 2010; Zhai et al., 2010; Yu et al., 2014). The assessment reports showed that droughts affected an average of $20.9\times10^4$ $km^2$ of cropland annually from 1949 to 2013, which accounts for one sixth of the total arable land in China. From 1991 to 2013, the yield loss of grain crops suffered from droughts was an average of $26.75\times10^9$ kg per year. From 2004 to 2013, the direct economic losses caused by drought averaged to 63.67 billion Yuan (10 billion dollars approximately) annually. In addition, the projection suggested that risks of extreme droughts will increase in most of China along with global warming in the future (Qin et al., 2015).

Recently, there are more and more studies focusing on the long term droughts events reconstruction and extreme droughts identification using high-resolution proxy data (such as historical documents, tree rings, etc.) at local, regional, and nationwide scales, and found the extreme droughts could cause tremendous impacts on agriculture, livelihood, even the societal system (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 the droughts in 1876–1877 led to 45% and 50% harvest reduction in 1876 and 1877 respectively, caused the rice price increased by 5–10 times than that in the normal year, and finally resulted in more than 13 million people died from famine and plague. Zheng et al. (2014a) found that the severe droughts occurring in 1627–1643 triggered a wide peasantry uprising, and also played a significant role to promote the peasantry 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 for 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 there existed a high positive correlation between temperature and grain yield. Bumper harvest decades corresponded to the warm-normal or warm-wet climate, while poor harvest decades occurred in the context of cold and dry climate. Yin et al. (2015, 2016) further demonstrated that from 210 BCE to 1910 CE, the poor harvest was mostly coincided with cold stage when climate changed from warm to cold along with dry or from wet to dry, while grain harvests increased in the warm phase. However, these studies didn't explore the impacts of extreme droughts on the harvest clearly, thus obscured well understanding on 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, we present a study here to further investigate the impacts on harvest caused by extreme drought and flood in eastern China from 801 to 1910, using the reconstructions for regional grain harvest grade and extreme drought/flood event derived from Chinese historical documents. The aim of our study is to identify the relationship between poor harvest and extreme drought/flood for the whole study period at first, then to illustrate whether there are any differences in that relationship between cold and warm periods, e.g. Medieval Climate Anomaly (MCA, 950–1250) and Little Ice Age (LIA, 1450–1850) (IPCC, 2013).

Clim. Past Discuss., https://doi.org/10.5194/cp-2019-14
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## 2 Data and Method

### 2.1 Data

Two datasets were used in this study, including the chronology of regional extreme drought and flood and the series of grain harvest grade. 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-statations since 137 BCE in eastern China (east of 105°E; 25ºN–40°N approximately), which were 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). The records for reconstruction of annual drought/flood grade at 63-statations were extracted from the historical documents, including "Twenty-Four Histories" and "Qing History Draft" (i.e., the official books about the history for each dynasty in China), chronicle, miscellaneous historical books, local gazettes and others. For example, in both *the Book of Tang* and *New Book of Tang* (two of "Twenty-Four Histories"), the documents at the 19th year of emperor Zhenyuan in Tang Dynasty (803 CE) recorded: In day 25 of the 6th month (in Chinese lunar calendar, i.e., Jul. 17, 803 in Solar calendar; same hereinafter), it was no rain in Guanzhong area (Now Xi'an and its surrounding areas) from the 1st month (Jan. 27-Feb. 24) till now, hundreds of officials and many people were praying for rain. In day 26 of the 7th month (Aug. 18), rain. In day 17 of the 8th month (Sep. 6), rain heavily. From mid-autumn, drought occurred again. These descriptions provided the information of drought with duration, spatial coverage and intensity clearly. Noted that drought in this year was also recorded in *the Corpus of Huangpu Chizheng* (written by Huangpu Chizheng, who lived in 777–835) and *the Complete Prose Works of the Tang Dynasty* (edited by Dong Gao who lived in 1740–1818), which provided different sources for cross-validation, and thus increased the reliability of records. Fig. 2 further showed a copy quoted from local gazettes, which recorded anomalous climate information for a given district (such as a County, Prefecture or Province) usually. From this sample, the readers could find the duration and intensity of drought or flood occurred in Prefecture Yangzhou, e.g., in 1848, there were 3-times of heavy rain, which caused floods in months from the 6th to 8th. In 1856, there was a severe drought from the 5th month to the 8th month, which led to the Grand Canal dried up (see more information in the Figure caption). Based on these records, Zhang (1996) reconstructed the dataset of 63-statations annual drought/flood grades. The introduction of this grade dataset has been summarized by Zheng et al. (2006) and Hao et al. (2016), including the criteria (i.e., the ideal frequency of 10% for grade 1/severe drought and grade 5/heavy flood respectively, 20% for grade 2/drought and grade 4/flood respectively, 40% for grade 3/normal year) and method for the drought/flood grade calibration, the spatial distribution of missing data, and its advantage compared with other datasets in spatio-temporal coverage and time-resolution. For example, compared with the dataset of yearly dryness/wetness grades (1=very wet, 2=wet, 3=normal, 4=dry, 5=very dry) for 120 stations over China from 1470 to 1979 (Academy of Meteorological Science of China Central Meteorological Administration, 1981), this dataset spanned a longer time. Compared with the series of regional dry/wet grades in six areas (usually consisted of more than 100 counties) from the Lower Yangtze Valley to the North China Plain during 960-1992

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(Zhang et al, 1997), this dataset covered more areas with a higher spatial resolution for local stations (usually consisted of 20 counties approximately).

Since there existed missing data in each sub-region (i.e., North China Plain, Jianghuai and Jiangnan shown in Fig. 1), the extreme drought and flood years were identified with both the coherence of drought/flood grade for individual station and percentage of each drought/flood grade occurrence within the available data of drought/flood grade in each sub-region. In detail, the extreme drought (or flood) year in a sub-region was defined with two terms: (1) grade 3 occurred in less than 25% of all stations; (2) grade 1 (or grade 5) and grade 2 (or grade 4) occurred in more than 80% of all stations (the stations with grade 3 or missing data were excluded), and grade 1 (or grade 5) occurred in 2 or more neighbouring stations. The validation has been conducted in the paper of Hao et al. (2010a), and showed that the years of extreme drought and extreme flood identified by this criteria for 1951–2000 (i.e., instrumental period) well matched with that identified by the threshold for probability of 10% and 90% occurrence based on the series of precipitation observation in each sub-regions. It demonstrated that the criteria used for identification of sub-regional extreme drought (or flood) year in historical times was 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 often adopted in other studies focusing on extreme climate.

Furthermore, the extreme drought (or flood) year for the whole eastern China was defined by the extreme drought (or flood) year from 3 sub-regions altogether, and the dry-wet index series over whole eastern China reconstructed and renewed by Zheng et al. (2006, 2014c) synthesizing the annual drought/flood grade from all 63-stations. The criteria to define extreme drought (or flood) year for the whole eastern China were: extreme drought (or flood) occurred in all 3 sub-regions; or extreme drought (or flood) occurred in 2 sub-regions and no extreme flood (or drought) occurred in the other sub-region; or extreme drought (or flood) occurred in only one sub-region and the dry-wet index for the whole eastern China in that year was lower (greater) than the mean of that series by at least 1.282-times standard deviation (i.e., less than 10% probability of the drought or flood occurrence during the last 2000 years). Moreover, if there were both extreme drought and extreme flood occurred in different sub-regions within one year, that year was defined as extreme year with co-occurrence of extreme drought and flood. In addition, to illustrate the uncertainty of reconstructions for regional extreme drought/flood, the confidence levels of them were also assessed based on the percentage of years with data available at per 50 years interval, in which the full confidence is defined as the percentage more than 90%; very high confidence: 66.7%–90%; high confidence: 50%–66.7%; medium confidence: 33.3%–50%; and low confidence: <33.3%.

(2) The series of grain harvest grade. This series was reconstructed based on historical records collected from the "Twenty-Four Histories" and "Qing History Draft", which included the descriptions of yearly grain yield estimate (e.g., a golden bumper year, abundant, plentiful, not bad, slightly poor, poor, very poor, etc.) and the related information on 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 country scale from 206 BCE to 1910 CE (Su et al, 2014; Yin et al, 2015). The levels of yearly harvest 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 grading the documentary records (i.e., grain yield

descriptions and the related information) year by year were presented by Su et al. (2014) and summarized by Yin et al. (2015). The comparison and validation in their studies (Su et al., 2014; Yin et al., 2015) showed that this grade system corresponds to a harvest rating system in percentage defined by the government as a code in *the Collected Statutes of Qing Dynasty* ("*Da-Qing Hui-Dian*" in Chinese, were finally compiled in 1899, in which the definition of the harvest rating system was recorded in Vol. 21), in which "Very poor" corresponded to "below 40%" of harvest yield, "Poor" corresponded to 40%–50%, "Slightly Poor" corresponded to 50%–60%, "Average" corresponded to 60%–70%, "Near bumper" corresponded to 70–80%, "Bumper" corresponded to above 80%. As argued by Marks (1998), although it was unclear about how the 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 the 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 was believed that the harvest rating descriptions recorded in Chinese history could indicate the fluctuation of yearly grain yield well (Marks, 1998).

It was worth noting that the earlier it was, the more missing records existed, especially before 760 CE, in both the dataset of annual drought/flood grades for regional extreme drought/flood chronology and the series of grain harvest grade. Thus, the study period here for investigating the impacts on harvest caused by extreme drought and flood in eastern China was selected from 801 to 1910. Moreover, the 2000-year temperature series with decadal resolution over China (Ge et al., 2013) was also adopted here to identify the long-term fluctuation of cold and warm periods. This temperature series were reconstructed based on 28 temperature proxies using principal component (PC) regression and partial least squares (PLS) regression respectively (Ge et al., 2013) and the comparison showed that the pattern of long-term temperature change over China is roughly consistent with that in the Northern Hemisphere showed in IPCC (2013) as an overlap of multi-reconstructions since 850.

### 2.2 Method

(1) To illustrate the variation of the occurrences of regional extreme drought and flood from 801 to 1910, the moving-window frequency of extreme drought/flood years in three sub-regions and whole eastern China were calculated with window of 50 years and step of 10 years at first. Then, the Wilcoxon rank sum test was applied to examine which interval has significantly more or less drought/flood years compared with all the other intervals. This is because the mean of rank series in an interval was equivalent to the frequency of drought/flood years when the chronology of extreme drought and flood years were converted into rank series by labelling the extreme drought (or flood) years as 1 and non-extreme years as 0.

(2) To examine whether the occurrences of extreme drought/flood in each sub-region and whole eastern China were connected to poor harvest, the 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 whole eastern China. Then the two-sampled t-test was applied to examine whether the means of harvest grade in extreme drought (or flood) years and non-extreme years are significantly different or not. Meanwhile, the contingency

table and Chi-square test ($\chi^2$) were adopted to examine the effects of regional extreme drought/flood on harvest for each grade. For example, corresponding with 720 years with harvest grade data available, there were 97 extreme drought years, 82 extreme flood years, and 541 non-extreme years in North China Plain. To examine whether the occurrence of poor harvest (grade 2) became significantly more in extreme drought years compared with non-extreme years for this sub-region, we made the contingency table by counting the 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. Then the chi-square test ($\chi^2$) was 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, we also calculated the frequency of extreme drought/flood years and performed the Wilcoxon rank sum test for the cold and warm periods in three sub-regions and whole eastern China. Similarly, the contingency table and Chi-square test ($\chi^2$) were also adopted to examine if there exist significantly different effects of regional extreme drought/flood on harvest between cold and warm periods.

## 3 Results and Discussion

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

Figure 3 showed the chronology of extreme drought/flood years and its variation for each sub-region (i.e., North China Plain, Jianghuai and Jiangnan area) and whole eastern China during 801-1910. In total, there were 133, 95, 90 extreme drought years and 113, 118, 119 extreme flood years occurred in North China Plain, Jianghuai, and Jiangnan area, respectively (Table 1). The comparison showed that the occurrence of extreme drought was a bit more frequent than that of extreme flood in North China Plain due to its sub-humid climate, while there were slightly fewer extreme drought years than extreme flood years in Jianghuai and Jiangnan areas due to their humid climate. For the whole eastern China, there were 126 extreme drought years and 122 extreme flood years, and 20 extreme years with co-occurrence of extreme drought and flood in different sub-regions.

Moreover, the moving-window frequencies of extreme drought/flood years during each 50-year by the decadal step showed that there existed remarkable multi-decadal variation on both extreme drought and flood occurrences in each sub-region and whole eastern China from 801 to 1910 (Fig. 3). In 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 area, 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 area, 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 whole 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 were 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 showed the series of grain harvest grade from 801 to 1910. There were missing data in 390 years (35.1% of all years); and the 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) respectively (Table 2). In total, the percentage of all poor harvest years (i.e., including grade 1, 2 and 3) was 39.3%, while the percentage of both bumper harvest years (i.e., including grade 5 and 6) was only 11.2%. Moreover, the moving-window percentage of each harvest grade and data missing for each 50 years with decadal step (Fig. 4b) showed that there was an evident jump around 1640s with the increase of years of grade 4 and decrease of data missing years. This was mainly because the "Qing History Draft" recorded more "average" harvest years and most of "average" records were excluded in "Twenty-Four Histories" due to the principle of "recording unusual rather than common events" as argued in Yin et al. (2015). Therefore, to avoid the effect of data missing and maintain the homogeneity in statistics, years of data missing and "average (grade 4)" were excluded in statistics, as adopted in Zheng et al. (2006), to re-calculate the relative percentage in each 50-year moving-window for years with poor and bumper harvest in total years of them (Fig. 4c) for illustrating the variation of grain harvest during 801-1910. By excluding grade 4 and missing data years, the relative percentages for each harvest grade in 801–1910 (i.e., whole period) were 9.6% (grade 1), 31.8% (grade 2), 36.4% (grade 3), 13.8% (grade 5), and 8.4% (grade 6) respectively (Table 2). Noted that, in Fig. 4c, we combined grade 1 and grade 2 (hereafter, "grade 1+2") as the poor group, and grade 5 and 6 (hereafter, "grade 5+6") as the bumper group, since the percentages for the occurrences of grade 1 and grade 6 were only 4.9% and 4.2% in all years respectively. For the entire period, the relative percentages of grade 1+2 and grade 5+6 were 41.4% and 22.2%, respectively.

The comparison between occurrences of poor and bumper harvest (Fig. 4c) showed that the grain harvest for 801–1910 could be divided into 5 periods roughly. From 801 to 940, the grain harvest was roughly poor with less occurrences of bumper harvest (only 7.1% for grade 5+6) but more occurrences of slightly poor harvest (51.4% for grade 3). From 951 to 1250, there were more occurrences of bumper harvest (31.9% for grade 5+6) along with relatively less occurrences of poor harvest (37.7% for grade 1+2, 30.4% for grade 3), except in 1121–1170 when the occurrences of harvest grade was similar to that in the $9^{th}$ century. From 1251 to 1650, there were prominent more poor harvest (63.1% for grade 1+2) but barely bumper harvest years (9.2% for grade 5+6). While in 1651–1840, there were more occurrences of bumper harvest (53.5% for grade 5+6) but less poor harvest (9.3% for grade 1+2). After 1841, the grain harvest became roughly poor again with less occurrences of grade 5+6 (9.1%) but more occurrences of slightly poor (63.6% for grade 3). On the whole, the harvest was roughly higher in 951–1250 corresponding to the warm climate and lower in 1450–1650 corresponding to the cold climate as argued in Yin et al. (2015, 2016). However, the harvest were higher again in 1651–1840 which corresponds to a cold climate.

Clim. Past Discuss., https://doi.org/10.5194/cp-2019-14
Manuscript under review for journal Clim. Past
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**3.2 The effects of regional extreme drought/flood on harvest during 801-1910**

Table 3 showed the mean of harvest grade for all extreme drought/flood years and non-extreme years for 3 sub-regions and whole eastern China during 801–1910, in which it was 3.3 for all non-extreme years over whole eastern China, with a little difference in 3 sub-regions. The two-sampled t-test showed that the mean of harvest grades for all extreme drought years was significantly lower than that for non-extreme years, which were 2.95 for all extreme drought years in whole eastern China, with 2.84 for North China Plain, 2.89 for Jiangnan, and 2.99 for Jianghuai. However, no significant difference was detected for extreme flood years for any sub-regions. These results indicated that more occurrence of extreme drought in any part of eastern China could lead to significantly reduced harvest in the long term average, yet more occurrence of extreme flood seemed to have no significant impact on harvest yield on average. This is mainly because that the occurrences of extreme droughts usually covered an immense area dominated by the large-scale single air mass, which could lead to significant impacts on agriculture extensively. On the contrary, occurrences of extreme floods were mostly caused by the rainstorms induced by the confrontation of air masses, which usually occurred in a belt-like area with a relative narrow extension. Meanwhile, the rainstorms could provide more water resources for agriculture in the surrounding area of extreme floods and thus improve the grain yield, which finally lead to a limited impacts of extreme floods on harvest for an immense area (Zhang, 1982). However, the mean harvest grade in the co-occurrence years of extreme drought and flood for the whole eastern China was merely 2.53 (Table 3), which was much lower compared with 3.30 for non-extreme years. This implied that the co-occurrence of extreme drought and extreme flood in different sub-regions at eastern China in the same year had a greater impact on harvest yield.

To illustrate the connection between harvest and regional extreme drought/flood, we showed the frequency of each harvest grade (i.e., the percentage of the years with each harvest grade accounting for all years without data missing) for extreme drought/flood years and non-extreme years at each sub-regions and whole eastern China in Table 4. It was found that the frequency of poor harvest (grade 1+2) for extreme drought years in North China Plain significantly increased from 29.2% (for non-extreme years, hereinafter) to 49.4%, with the frequencies of grade 1 and grade 2 significantly increasing from 6.3% and 22.9% to 13.4% and 24.0%, respectively. Compared with non-extreme years, although the extreme drought in Jianghuai didn't cause significant increase in frequency of grade 1 or grade 2, respectively, it caused significant increase in the frequency of grade 1+2 (poor harvest) from 31.5% to 41.9%, and 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%, respectively. When extreme droughts occurred in whole eastern China, it was shown that not only the frequencies of grade 1 and grade 2 both increased 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 shown that the co-occurrence of extreme drought and flood in whole eastern China had greatest impact on harvest, which led to the frequency of grade 2 significantly increase from 22.4% to 60.0%, though there only existed at certain years. In summary, more occurrence of extreme drought in any sub-region of eastern China could lead to significant increase of frequency of poor harvest (grade 1+2) compared with non-extreme years.

However, the connection between harvest and extreme flood seemed to be much weaker. No significant difference was found between frequency of poor harvest in extreme flood years and non-extreme years, although extreme floods could cause significant decrease of frequency for bumper harvest in some cases. Specifically, extreme floods in Jianghuai and Jiangnan both led to significant decrease in the frequency of grade 5 (near bumper) from 12.2% and 11.9% to 5.7% and 5.6%, respectively. Possible cause for this connection is that rainfall is sufficient to crop growth in these two humid areas in usual, thus extreme floods had negative impacts on potential bumper harvest (Zheng and Huang, 1998).

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

To illustrate whether there were any differences of the occurrence of regional extreme drought/flood and their effects on grain harvest between warm and cold periods, we presented multi-proxies-based temperature reconstruction with a decadal resolution over China in Fig. 3e. It was suggested that temperature over China for 801–1910 had experienced two long-term anomalous epochs though both of them included several multi-decadal fluctuations, including warm in 920-1300 and cold in 1310-1880 (Fig. 4), in which the first one covered Medieval Climate Anomaly (MCA, 950–1250) and the latter covered Little Ice Age (LIA, 1450–1850) identified by IPCC (2013).

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

As found in section 3.2, more occurrence of extreme drought in eastern China could lead to significant increase of frequency of poor harvest (grade 1+2) compared with non-extreme years. Since there were more extreme droughts occurred over eastern China in 920–1300 compared to 1310–1880, the harvest in warm epoch should be worse than that in cold epoch. However, as found by Yin et al. (2015, 2016), the harvest in warm epoch was better than that in cold epoch. This implicated that there should be different effects of regional extreme drought on grain harvest between warm and cold epochs. For illustrating the difference, Table 6 showed the frequency of poor harvest (grade 1+2) occurrences in extreme drought/flood years and non-extreme years for warm and cold epoch, i.e., 920–1300 and 1310–1880. Noted that there existed a shift in the distribution of each harvest grade since 1650 due to the increase of years with grade 4 and decrease of years with data missing. Thus, the connection between poor harvest (grade 1+2) and regional extreme drought for 1650–1880 were also

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investigated. The results showed that, during the warm epoch of 920–1300, the connection between the occurrence of poor harvest and regional extreme drought was not significantly close, though the frequency of poor harvest in extreme drought years was still slightly higher than that in non-extreme years for each sub-region. By contrast, during the cold epoch of 1310–1880, the frequency of poor harvest in extreme drought years was significantly higher than that in non-extreme years, which indicated that the connection between the occurrence of poor harvest and extreme drought was still significant. Moreover, similar characteristics were also found for the latter half of cold period in 1650–1880, which indicated that the shift of harvest grade distribution didn't affect the connection between poor harvest and extreme drought/flood in cold epoch. These results suggested that warm period could weaken the impact of extreme drought on poor harvest during historical times. Possible cause might be that, during the historical times with limited and low adaptability, the warm climate provided more thermal resources and extended growing season, thus further increased the multiple cropping index and provided more thermal-limited lands for crop plant, which permitted people to have more options to adapt the climatic variation, and finally mitigated the impacts of extreme drought on harvest. As assessed by Zhang (1982) based on the data from 1909 to 1979, the harvest may change by approximately 10% if the temperature changed by 1°C on national scale, in which the harvest increased significantly in 7 of 8 warm years. However, the cold climate could limit the multiple cropping and shrink the area of arable land, which lead to the harvest become more vulnerable to extreme droughts. Moreover, as reported by Zhang et al. (2007), the limited resources could also cause many social turbulences, such as famine, peasantry uprising, war outbreak, and population decline, which may further enhance the vulnerability for agriculture. Therefore, even though the occurrence of extreme drought is slightly more frequent in the warm period of 920–1300, the frequency of poor harvest did not increase significantly.

### 3.4 Discussion

Chinese historical documents provide a unique proxy for reconstructions on climate change and annual harvest grade, which enable us to investigate the impacts of climate change on grain yield back to thousand years ago. Compared with previous study (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, our study presented a case to examine the impacts of extreme drought/flood on grain harvest and their difference between warm and cold periods year by year. Thus, our study could improve the understanding on the climatic impacts on agriculture induced by short-term extreme events in context of long-term temperature change. Especially the finding on the non-significant connection between occurrence of poor harvest and regional extreme drought in warm climate may help to further explore the implications on adaptation for agriculture to future global warming along with more extreme climate probability.

However, there still existed several issues that could lead to uncertainty of our study. First, the reconstructed chronology of regional extreme drought and flood may not include all events due to the missing records before 1400. 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) were in low confidence. Moreover, the

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reconstructed chronologies for 1150–1200 in North China Plain, 1200–1250 in Jianghuai, and 800–850, 950–1100 in Jiangnan were also in medium confidence. Thus, the most of reconstructed chronology of extreme drought and flood for whole eastern China before 1400 was below medium confidence. Second, there may also be limitation in the grading of annual harvest for some years. For example, in 1181, the harvest was assessed as grade 6 according to the description of "It is a plentiful year after sufficient rainfall kill locusts" from *History of Song* (one of "Twenty-Four Histories"), which usually recorded the events for country-wide. Thus, it was regarded as a record for national scale usually. However, as recorded in *Compilation of Essential Regulations of the Song Dynasty* ("*Song Hui-Yao Ji-Gao*" in Chinese, edited by Xu Song, Vol. 66, Vol. 69), there were lots of "drought" occurred in southern China in that year which led to poor or slightly poor harvest in at sub-regional scale. Similar cases were also found in 1032, 1073, 1353, and 1638. These cases suggested that the grain harvest descriptions recorded in "Twenty-Four Histories" may not indicate anomalous harvest for all years at the national scale. These limitations may induce uncertainty to this study by affecting the statistical relationship between harvest and extreme drought/flood. Therefore, further study is needed, especially to find more historical records from the other scattered documents for supplement the evidences recorded in "Twenty-Four Histories".

## 4 Conclusion

The changes of regional extreme drought/flood occurrences and grain harvest, and their possible connection were investigated for 801–1910 using reconstructed chronology of regional extreme drought/flood and the series of grain harvest grade. Results showed that there were significantly more extreme droughts in 801–870, 1031–1230, 1481–1530 and 1581–1650, as well as more extreme floods in 811–840, 951–990, 1051–1070, 1381–1430, 1641–1670, 1721–1770 and 1810–1870 over whole eastern China, with different phases in 3 sub-regions, including more extreme droughts 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 roughly poor in periods of 801–940, 1251–1650 and 1841 to 1910, but bumper in periods of 951–1250 and 1651–1840 approximately. Both of t-test and Chi-square test ($\chi^2$) demonstrated that more extreme droughts in any sub-regions of eastern China could lead to significantly more poor harvest, and co-occurrence of extreme drought and extreme flood in different sub-regions at eastern China in the same year could result in a greater impact on harvest yield, yet the occurrence of extreme flood seemed to have no significant impact on harvest yield in the long term average. Moreover, the comparison showed extreme droughts over whole 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 harvest in extreme drought years was still slightly higher than that in non-extreme years for each sub-region. This is mainly because the warm climate could provide more thermal resources and extend growing season to increase the multiple cropping index and more thermal-limited lands for crop plant, which permitted people to have more options to mitigate the impacts of extreme drought on harvest. Thus, our study could provide a case to further explore the implications on agricultural adaptation to future global warming along with more extreme climate probability.

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

**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.

**Acknowledgements.** This study was supported by the National Key R&D Program of China (2017YFA0603301), the National Natural Science Foundation of China (41671036, 41831174) and the Strategic Priority Research Program of the Chinese Academy of Sciences (XDA19040101).

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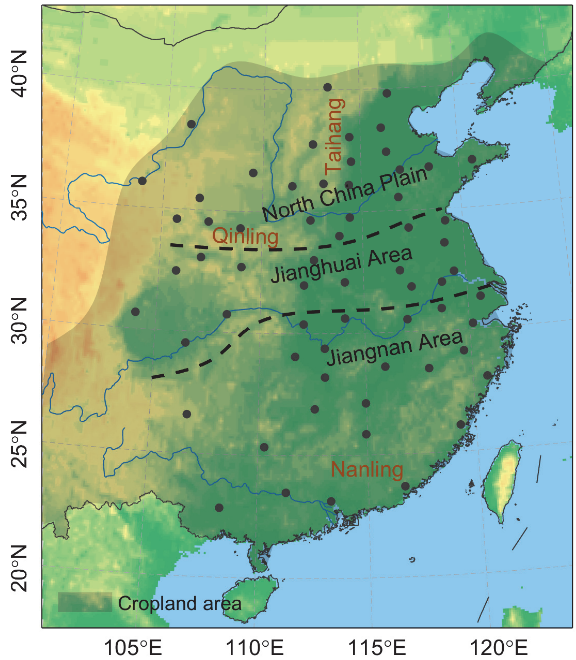


**Figure 1: Location of 63 stations with drought/flood grade data and sub-region divisions. The grey area indicated the region with cropland distributed approximately during 801–1910.**

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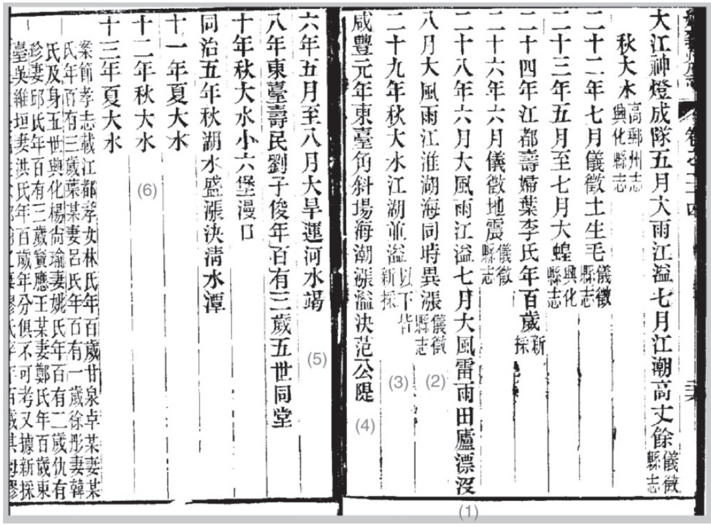


**Figure 2: An example of anomalous climate information recorded in local gazettes (Quoted from Gazettes of Yangzhou Prefecture compiled in 1874). The two pages list the anomalous climate information in the region from 1842 to 1874 (from right to left), dated with Chinese lunar calendar. The numbers in brackets are added by us to show the meaning here as the examples of records. (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 the strong wind and thunder storm, field 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 the records of "strong wind" and "the sea level abnormally rose" also suggested the heavy rain was induced by a typhoon. (3) It was 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 above records were quoted from earlier local gazettes. (4) The 1st year of Xianfeng emperor (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 month, it was severe drought and the Grand Canal dried up. (6) Autumn of the 12th year of Tongzhi emperor (1873), it was flood.**

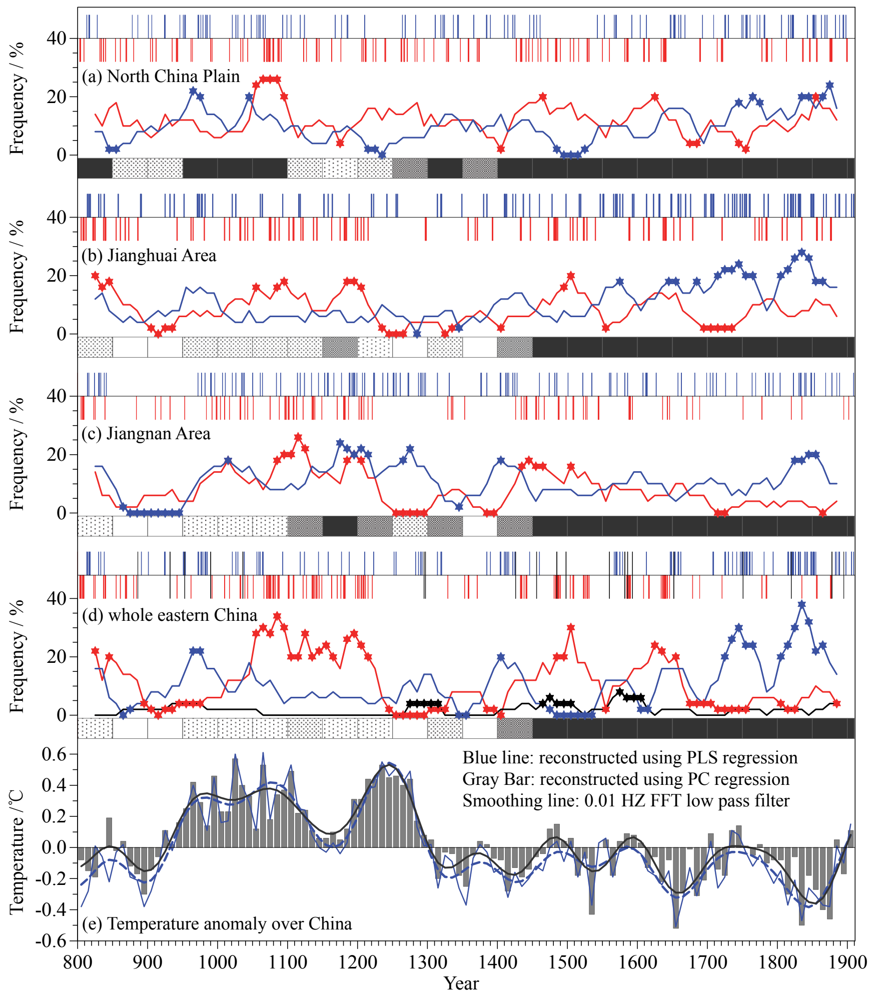


**Figure 3: The chronology (vertical line in top row of each plate) and frequency (star-line, 50-year moving-window with decadal time step) of extreme drought (red) and flood (blue) for sub-region of North China Plain (a), Jianghuai (b), Jiangnan area (c) and whole eastern China (d) during 801–1910. Black line in plate (d) indicates same frequency but for the co-occurrence of extreme drought and flood for whole eastern China. Stars: intervals with significant more or less extreme drought and flood compared with all the other intervals by the Wilcoxon rank sum test. Bars at bottom row of each plate illustrated the confidence levels (full confidence: dark; very high confidence: 50% shaded dark; high confidence: 25% shaded dark; medium confidence: 12.5% shaded dark; and low confidence: blank) for each reconstructions at per 50 years. (e) The temperature series over China (at decadal resolution) for comparison, which were reconstructed based on 28 temperature proxies using principal component (PC) regression and partial least squares (PLS) regression respectively (Ge et al., 2013).**

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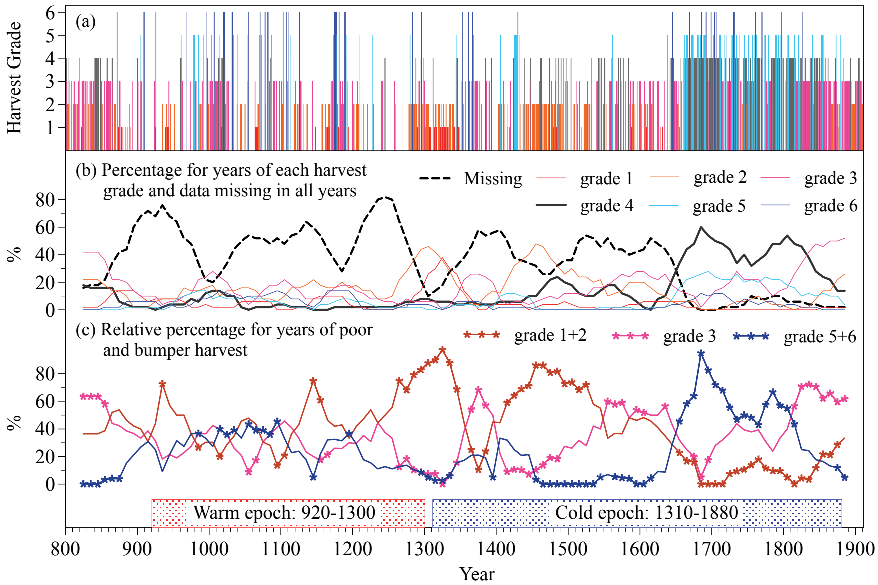


**Figure 4: (a) The yearly harvest grade from 801–1910, 1-Very poor (red), 2-Poor (orange), 3-Slightly poor (pink), 4-Average (black), 5-Near bumper (light blue), 6-Bumper (blue). (b) The variation of percentage for the years with each harvest grade and data missing using a moving-window of 50 years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

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**Table 1: Frequency of extreme drought and flood occurred in each sub-region and whole eastern China from 801–1910.**

| Sub-region | Extreme event | Years occurred | 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 |

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**Table 2: The years and percentage for each harvest grade and data missing from 801 to 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 | - |

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**Table 3: The comparison between the mean of harvest grades in extreme drought/flood years and non-extreme year for 3 sub-regions and whole 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 eastern China | 3.30 | **2.95**$^{**}$ | 3.27 | **2.53**$^{**}$ |

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

**Table 4: The comparison on frequency of each harvest grade between extreme drought/flood years and non-extreme years from 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 | |

The value in bold with stars denote significant more or less (also in italic) occurrences by Chi-test ($\chi^2$) 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: The comparison on frequency of extreme drought/flood between warm and cold epoch.**

| Sub-Region | | Frequency (%) Warm epoch 920-1300 | 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 |

The value in bold with stars denote significant more or less (also in italic) frequent extreme drought/flood in 920–1300 compared with 1310–1880 by rank sum test at level of: ***, p<0.01; **, p<0.05; *, p<0.1.

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**Table 6: The comparison on frequency of poor harvest (grade 1+2) occurrences between 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 |

The value in bold with stars denote significant more occurrences by Chi-test ($\chi^2$) at level of: ***, p<0.01; **, p<0.05; *, p<0.1.