Reconstruction and analysis of extreme drought and flood events in the Hanjiang River basin since 1426

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15   **Abstract:** The major droughts and floods in the Hanjiang River basin have a significant impact on the flood prevention and control in the middle reaches of the Yangtze River and water resources management in the areas of the South-North Water Diversion Middle Line Project of China. However, there is a lack of understanding of the multi-decadal to century-scale patterns of droughts and floods in the Hanjiang River Basin. Applying the yearly drought and flood grades reconstructed based on historical documents, and the criteria developed for identifying extreme droughts and floods in historical periods,

20   this paper constructs a time series of extreme droughts and floods (i.e., the event with occurrence probability less than 10% from 1951-2017) in the Hanjiang River basin from 1426-2017. The possible linkages of the extreme droughts and floods with Asian monsoon (i.e., East Asian monsoon and South Asian monsoon), strong ENSO (i.e., El Niño and La Niña) and large volcanic eruptions are also discussed. The results show that there were 45 extreme droughts and 51 extreme floods in the Hanjiang River basin over the past 592 years. The frequency of extreme droughts was high during the 15th century, early

25   16th century, the 17th, and the 20th centuries, with the 20th century being the highest. For extreme floods, the frequency was high in the 16th century, the 17th century, the 19th century, and the 20th century, with the 19th to 20th centuries being the highest. The 18th century was a common low period of extreme droughts and floods, while the 20th century saw a high frequency of both. When the Asian monsoon is weak, extreme droughts were more likely to occur; and when the Asian monsoon is strong, extreme floods were more likely to occur. Furthermore, on multi-decadal scale, extreme floods were

30   found to become more frequent with the increase in numbers of strong El Niño events and large volcanic eruptions. These results are informative for the study of mechanisms and predictability of decadal to century scale variability of extreme hydro-climatic events in the Hanjiang River basin.

35   **1 Introduction**

   Extreme droughts and floods often severely impact agricultural production, people's livelihoods, and socio-economic development. Throughout the history of human development, there have been "almost no years without disaster" (Deng, 1958). In the historical records of natural disasters in China, droughts and floods dominate in particular, showing their

40   tremendous impact on the society and economy.

   According to the IPCC Fifth Assessment Report (AR5), the global mean surface temperature showed a significant upward trend from 1880 to 2012, increasing by 0.85°C, and the global temperature increase in the 21st century will probably exceed 1.5-2.5°C (IPCC, 2013). Temperature increases not only directly affect changes in temperature extremes but also lead to changes in the frequency of regional extreme climate events such as droughts and floods (Dai, 2013., Goswami et al., 2006)

45   Observational studies have shown an increasing trend in precipitation over much of North America, Europe, central North Asia, eastern South America and Oceania during 1901-2010. However, decreasing trends of precipitation have been

observed in northern Africa, the Mediterranean, southern Africa, and much of eastern and southern Asia. Meanwhile, there have been more prolonged and more intense drought events in southern Europe, West Africa and other places (IPCC, 2013). In China, since the late 1970s, the eastern region showed a pattern of "south floods and north droughts" (Sun and Chen, 2003; Hsu et al., 2014), with precipitation in northern China, southwestern Northeast China and eastern Northwest China going to decrease. In contrast, precipitation and heavy rainfall in the Yangtze River basin and southeast coastal areas increased (Ding et al., 2008; Zhang et al., 2008; Wang and Fan, 2013). However, since the beginning of the 21st century, the precipitation pattern in the eastern part has shown a reversal trend, with the precipitation in the Yangtze River Basin decreasing significantly, the precipitation in North China and southwestern Northeast China beginning to increase, and the drought in Southwest China intensified (Ren et al., 2015; Ding et al., 2020).

An essential scientific question currently facing the academic community is how extreme precipitation, droughts and floods will change in East Asia in the future under global climate warming? What are the differences in future extreme precipitation events in different large river basins in eastern China's monsoon region? Climate model simulations and observational studies based on historical series of precipitation, drought and flood data are the primary means for understanding the patterns and mechanisms of decadal to century scale variability in precipitation and droughts/floods. Meanwhile, understanding the patterns and mechanisms of past precipitation variability is a prerequisite for predicting future precipitation and extreme precipitation. In particular, the long series of climate data can be used to study patterns of historical precipitation and drought/flood variation, and they are also essential for testing the climate models used for future climate predictions. Therefore, the long-term observations or proxy data of the past hundred to several hundred years or more at different spatial scales are first required to meet the demand of the studies.

In most parts of the world, especially in eastern China's monsoon region, however, the duration of instrumental meteorological data is less than 100 years. Furthermore, instrumental observations are extremely scarce in the early 20th and late 19th centuries, and only sporadic climatic records before the mid-19th century were available, making it impossible to satisfy studies of historical precipitation and droughts/floods variability. Therefore, using long-term high-resolution historical drought and flood records to reconstruct the sequence of extreme precipitation, drought and flood events at basin and regional scales are scientifically essential for studying the patterns and mechanisms of climate variation in historical periods (IPCC, 2012, 2013; Cook et al., 2010; Ge et al., 2016; Mikami, 2008).

China has a wealth of continuous historical documents that provided precious material for studying climate change in historical periods, with the wealthiest records of historical droughts and floods (Zheng et al., 1993). Since the 1970s, Chinese scholars have used historical data on droughts and floods to reconstruct the time series of the past climate and extreme climate, achieving fruitful research results. From the mid to late 1970s to the early 1980s, for example, the Institute of Meteorological Sciences of the Central Meteorological Bureau, in cooperation with the relevant institutions, compiled and completed the "The Atlas of Drought and Flood Distribution in China in the Last 500 Years", by applying drought and flood records in the historical documents such as local chronicles, the Forbidden City archives and chronologies of disasters through the ages (Zhang, 1981). For the same period, Wang and Zhao (1979), Zhang and Gong (1979) and Zhang (1989) studied precipitation and drought/flood variations in historical periods using chronological data on drought and flood grades for the last 500 years in China.

In recent years, the research results of historical droughts and floods have become more abundant. For example, Han and Yang (2017) used historical documents to reconstruct the sequence of wet and dry changes on the Loess Plateau from 1000-1949 AD. They analyzed the relationship between wet and dry change and extreme droughts on the Loess Plateau in the past millennium and its association with the Pacific Decadal Oscillation (PDO). Zheng et al. (2020) conducted a review of the characteristics of annual to centennial-scale changes in wet and dry conditions in China over the past millennium based on a series of new results published in recent years. They also provided a comprehensive assessment of the historical positions of the wet and dry variability of the 20th century. Based on data on drought/flood grades at 63 stations (regions) in eastern China for the past 2000 years reconstructed from historical documents, and an updated series of temperature changes in China reconstructed by integrating 28 proxies, Hao et al. (2010a) investigated regional differences in the frequency of droughts and floods under the background conditions of centennial-scale cold and warm periods.

Meanwhile, several studies had argued that the variability of precipitation over much of China is influenced by East Asian monsoon in conjunction with ENSO, and some studies suggested that large volcanic eruptions could also affect the inter-annual variability of precipitation. For example, Ding and Liu (2008) found a phase difference of about two weeks of the onsets between the Indian summer monsoon and the plum rains in the Yangtze River Basin of China. Li et al. (2016) showed that El Niño development years would decrease precipitation in most southern China, especially in the Yangtze River and its southern regions, while El Niño decay years will do the opposite. Huang et al. (1998) found that the 1998 summer mega-floods in the Yangtze River basin were influenced by the combined effect of tropical Pacific SST and snow accumulation on the Tibetan Plateau during the transition from maturation to decay of El Niño in the ENSO cycle. Liu et al. (1993) found a significant geographic variation in the effects of low- and mid-high latitude volcanic eruptions on the succeeding drought/flood and precipitation in China. They argue that, in general, northern China was significantly drier in the eruption year, with no significant precipitation anomalies occurring in the Yangtze River basin until the next year. Shen et al. (2007) indicated that the three most severe drought phases in eastern China over the past five centuries (1586-1589, 1638-1641 and 1965-1966) might have been caused by large volcanic eruptions and were simultaneously influenced by the amplified modulation effect of ENSO events.

However, most of the above studies examined characteristics of precipitation or drought/flood variations from a large spatial perspective. There are few studies using historical drought and flood records to explore the extreme precipitation patterns and mechanisms at a regional level, particularly in a medium to small scale river basin (e.g., Chen, 1987; Zhang et al., 2004; Ren et al., 2015). Due to the comprehensive influence of multiple factors such as topography and geomorphology, long-term precipitation variation characteristics in different regions and basins are usually not similar. Even within a medium to small scale basin, there are spatial differences in precipitation and drought/flood events in historical periods (Zheng et al., 1993). In the climatic transition zones, the spatial characteristics of climate change and variability are more complex.

Hanjiang River is one of the major tributaries of the Yangtze River. It is located in the northern subtropical climate zone to the south of the Qinling Mountains, and is in the transition zone between China's northern and southern climates, which is sensitive to climate and environmental change (Zhu, 1958; Miao et al., 2009). The drought, flood control and water supply in the basin are of great importance in the national socio-economic development and ecological restoration. As the water source area of the South-North Water Diversion Middle Line Project and a key river basin for flood control in the middle reaches of the Yangtze River, the Hanjiang River has a wide range of socio-economic impacts in terms of precipitation and drought/flood variability. Therefore, there is an urgent need for research on precipitation and drought/flood variability at the time scales of decadal to century in the Hanjiang River Basin (HRB). There were a few of previous studies on the HRB's historical precipitation, but most of them were focused on the upper Hanjiang River region, or conducted over relatively short periods, or reconstructed with low temporal resolution using proxy information such as lake and river sediments (Zhou et al., 2006; Huang et al., 2013; Zhou et al., 2014; Yin et al., 2015; Ding and Zheng, 2020). Therefore, research on the reconstruction of the high-resolution drought/flood series and their variation patterns in the HRB's historical period still needs deepening and refinement.

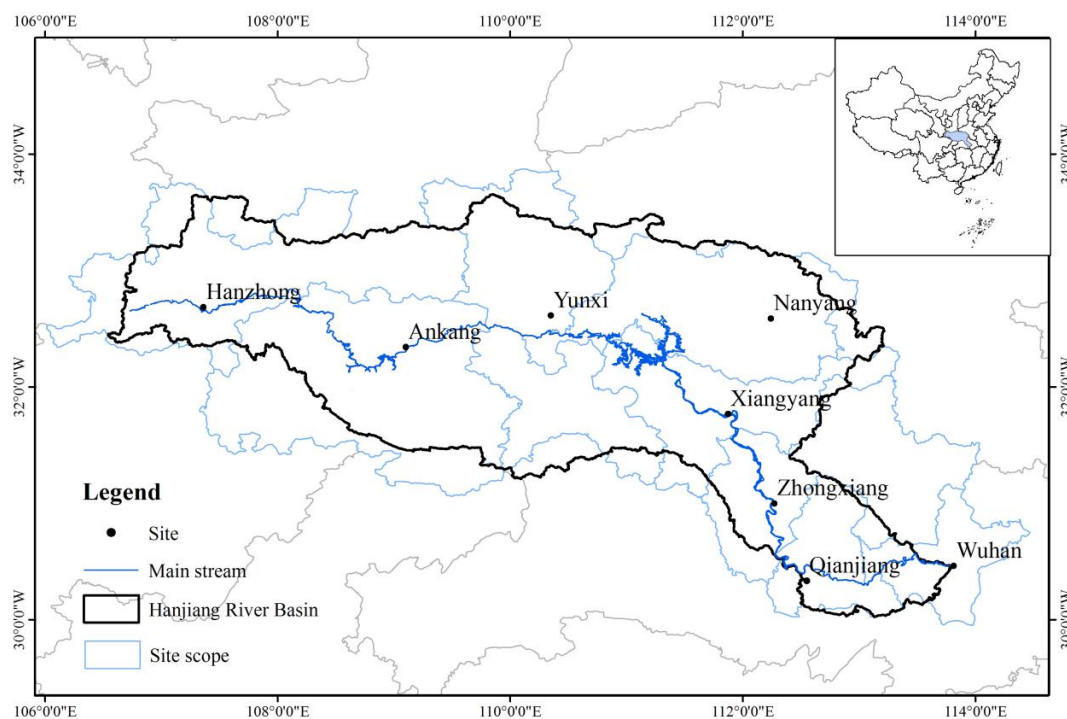
This paper reports a reconstruction and analysis of high-resolution historical extreme drought and flood time series over the Hanjiang River basin from 1426 to 2017. The results presented in the paper would be helpful for understanding the decadal to multi-decadal variability of extreme precipitation and drought/flood events in the important branch of the Yangtze River.

2 Research area, data and methods

2.1 Research area

The study area is the HRB (Figure 1). The Hanjiang River originated at the southern foot of the Qinling Mountains. It flows through Shaanxi, Henan and Hubei provinces before merging into the Yangtze River at Wuhan, with a total length of 1,577km, a basin area of 159,000km^2, average annual precipitation of 700-1300mm and an average annual runoff of 51.7 billion m^3 (Yin et al., 2015). HRB has a humid subtropical monsoon climate with a pronounced spatial difference of

140   precipitation. The annual precipitation increases from northwest to southeast and mainly concentrates in summer and autumn, with July to September accounting for about 70% of the annual total precipitation. Droughts and floods are both severe in the HRB, mainly because the river's upper reaches are mountainous, with narrow, deep, meandering channels and fast currents. Flash floods and prolonged droughts can cause severe impacts. In the middle and lower reaches of the Hanjiang River, the slow currents flow due to the low slope of the Jianghan Plain leads to unstable channels and inadequate discharge capacity,

145   resulting in frequent floods. Since the 1990s, the HRB has been experiencing continuous drought, severely impact the ecological environment, the rational allocation of water resources, and water supply in the basin.

150   **Figure 1: Study area and locations of the eight prefecture capitals used for reconstruction of drought and flood. The inset indicates the relative location of the study area in China**

2.2 Data

155   Four datasets were used in this study, including historical drought and flood records of the HRB, Asian Monsoon Index series, chronologies of strong ENSO and large volcanic eruptions.

(1) Historical drought and flood sequences and documentation

      The information used in this study to reconstruct the drought and flood sequences was divided into two parts: historical

160   data and instrumental data. Sources of historical data included local chronicles, Qing Dynasty archives (memorials, Shangyu) etc. Primary historical data source was "A Compendium of Chinese Meteorological Records of the Last 3000 Years" (Zhang, 2004). This collection of materials systematically compiled various kinds of written records on weather and climate in China for more than 3000 years from the 13th century AD to 1911 AD. In addition, other datasets were also collected and used, including "The historical Documents on Flood and Waterlogging of Southwest International Rivers in the Yangtze River

165 Basin in Qing Dynasty "(Yang and Guo, 1991), "The Disaster Annals in Modern China" and "The Continuation of Disaster Annals in Modern China (1919-1949) "(Li et al., 1990; 1993), "Zaixu Xingshuijinjain-Yangtze River Volume" (Wu and Zhao, 2004), and "Compilation of the Memorials to the Throne in Qing Dynasty: Agriculture·Environment "(Ge, 2005). The data were mainly derived from official documents, notes, letters, local chronicles, inscriptions, newspapers, magazines and river worker file transcripts of the Qing dynasty. Moreover, drought and flood records from 1911 to 1949 AD in "The China

170 Meteorological Disaster Dictionary" (Shaanxi Volume, 2005; Henan Volume, 2005; Hubei Volume, 2007) were also collected and used as supplementary data.

In terms of the overall distribution of information, the records of drought/flood in the local chronicles are more continuous and complete. They can also reflect information on the extent of disasters and disaster relief in each prefecture and county, effectively showing disaster's spatial distribution and temporal change. The archival information is of the highest credibility

175 (Ge and Zhang, 1990). It provides a primary basin-wide picture of droughts/floods with a clearer spatial and temporal resolution accurate to the county level.

The instrumental data comes from the monthly precipitation dataset "China National Ground Meteorological Station Homogenized Precipitation Data Set (V1.0)". This set of precipitation observations were quality controlled and tested, and adjusted for inhomogeitieies caused by non-climatic factors such as the relocation of stations and instrumentation. This study

180 uses precipitation data from 8 sites (Hanzhong, Ankang, Yunxi, Nanyang, Xiangyang, Zhongxiang, Qianjiang and Wuhan) in and around the HRB (Figure 1).

(2) Other historical data series

Asian monsoon index. The East Asian summer monsoon index dataset (1426-1949) reconstructed by the $\delta^{18}O$ content of

185 Vientiane Cave by Zhang et al. (2008) and the South Asian summer monsoon index dataset (1426-2000) reconstructed using Indian tree ring data by Shi et al. (2017) were used in this study.

ENSO Sequence Chronology (1525-2002). The El Niño and La Niña events in the historical ENSO chronology reconstructed by Gergis and Fowler (2009) from tree-ring, ice-core, coral records and historical documents were used. These El Niño and La Niña events were divided into five grades as extreme (E), very strong (VS), strong (S), medium (M), and

190 weak (W). This study selected VS and E grades as strong ENSO events. There were 45 strong El Niño and 56 strong La Niña events identified during 1525-2002.

Large volcanic eruptions (1426-2017). The chronology of large volcanic eruptions used in this study was derived from the volcanic eruption index series published by the Smithsonian Volcano Institute (Global Volcanism Program, 2020). This dataset includes information such as the volcano's location (latitude, longitude and altitude), the start and end time of the

195 eruption, ash volume and the volcanic eruption index (VEI). VEI integrated such parameters as type of eruption, duration, ash volume and height of the volcanic cloud column to measure the eruption's intensity. Compared with other reconstructed volcanic eruption indexes (e.g., Sigi et al. 2015), this dataset contained yearly volcanic eruption events. This study selected large volcanic eruptions with VEI ≅ 5, with a total of 45 years of large volcanic eruptions occurred from 1426-2017.

200 **2.3 Method**

(1) Reconstruction method of historical drought and flood

Based on the criteria of "The Atlas of Drought and Flood Distribution in China in the Last 500 Years" (Central

205 Meteorological Bureau, 1981), single-station and regional drought/flood series were established using the grading method. The degree of drought/flood or precipitation was divided into five grades: Grade 1-Flood, Grade 2-Mild Flood, Grade 3-Normal, Grade 4-Mild Drought, Grade 5-Drought. The drought and flood grades at each site indicated the degree of regional precipitation anomalies within a specific range represented by that site. Historical drought/flood grades were mainly based on historical records. In assessing the drought/flood grades for a region based on several drought/flood records for a

210 given year, the primary considerations were the precipitation conditions in spring, summer and autumn, as well as the timing, extent and severity of their occurrence. If there were droughts and floods within the representative area, the judgment would

be based on most counties' situation. If a site has a gap in records of less than 3 years, it is considered to have no drought or flood and was graded 3; a site with a gap in records of more than 3 years was not graded.

In order to take into account the frequency of occurrence of each grade, the ideal frequency criteria of 10% (Grade

215   1-Flood; Grade 5-Drought), 20%-30% (Grade 2 Mild-Flood; Grade 4-Mild-Drought), 30%-40% (Grade 3-Normal) (Central Meteorological Bureau, 1981) were used to adjust the classification of drought and flood grades in the HRB throughout the study period. When precipitation records were available, the May-September precipitation for the area where the site is located was used to be consistent with the frequency of drought and flood grades obtained from historical data. Table 1 shows the division criteria into various grades and their typical descriptions in historical sources and the criteria for grading

220   precipitation.

Table 1: Criteria for classifying droughts and floods and their typical descriptions in historical sources and criteria for grading precipitation in modern time

Event grade	Event Type	Criteria for historical records	Criteria for modern precipitation
1	Flood	Intense and prolonged precipitation, widespread floods and very heavy storms, such as: "Houses were swept away and overflowed, and countless people died in the floods";"The torrential rain continued for more than half a month and still did not stop. Houses and fields were flooded, people had to rely on boats to get in and out of the city" etc.	$Ri > (R + 1.7\sigma)$
2	Mild Flood	Sustained precipitation, local floods and hurricane rains that are not very severe and occurred in a single-season or single-month, such as: "It has been raining in the autumn, resulting in the crop failure or growing affected negatively"; "There was a flood in May" etc.	$(\bar{R} + 0.33\sigma) > Ri \leq (\bar{R} + 1.7\sigma)$
3	Normal	It is recorded as a harvest year, or droughts and floods are not recorded, such as: "The autumn harvest"; "A year of great harvest" etc.	$(\bar{R} - 0.33\sigma) < Ri \leq (\bar{R} + 0.33\sigma)$
4	Mild Drought	Single-season or single-month droughts that are less severe or localised, such as: "There was a drought this spring"; "The lack of rain in spring, in March, made seeding difficult" etc.	$(\bar{R} - 1.17\sigma) < Ri \leq (\bar{R} - 0.33\sigma)$
5	Drought	Drought lasting several months or inter-seasonal drought, widespread severe drought, such as: "Wells run dry, rivers cut off"; "There was a great drought, and people began to eat human flesh" etc.	$Ri \leq (\bar{R} - 1.7\sigma)$

225   Ri means May-September precipitation in a year, $\bar{R}$ means May-September average precipitation in a reference period, σ means standard deviation.

Using the above methods, according to the characteristics of the spatial and temporal distribution of drought/flood historical data in HRB, and following the principle of uniform spatial distribution and the enough amount of historical data, three sites of Xiangyang, Zhongxiang and Qianjiang were added, in addition to the 5 existing sites in "The Atlas of Drought and Flood Distribution in China in the Last 500 Years" (Central Meteorological Bureau, 1981). Thus, the total sites reached eight in the study region. The name of each site is the name of the county and municipality within the basin. However, the drought and flood it represents were not limited to the administrative area to which the site name refers and encompass a particular geographical area around it (Figure 1).

A total of 4328 records of droughts and floods in the HRB from 1426-1950 were collected from the above-mentioned historical documents. Historical documents have the common feature of "the closer to the present day, the more detailed and richer the record; the further from the present day, the less documented" (Zheng et al., 2014). Simultaneously, there are also sudden jumps in the number of records, which were mainly due to dynastic changes and technological progresses. In order to evaluate and correct the non-uniformity of the number of records over time, we counted the number of local chronicles and archives of the Ming and Qing dynasties in the study area with reference to the method reported in Yang and Han (2014). On this basis, a test of homogeneity at 95% confidence in the number of available data was conducted, which revealed a significant abrupt change in the number of records in 1812, indicating a significant increase in the number of local records and archival materials in the 1810s. Furthermore, after 1951, with the construction and development of the modern meteorological observation network, the number of meteorological observation stations in the HRB increased significantly, and precipitation observation began to enter the period of instrumental measurement, which represents a radical change in data category. Therefore, 1812 and 1951 were regarded as the time nodes of discontinuity in the temporal distribution of the data, respectively. Therefore, 1426-2017 were divided into three time periods: 1426-1812, 1813-1950, and 1951-2017. The eight sites' average recording rates during these three time periods were 61.11%, 91.28% and 100%, respectively (Figure 2). Because of the nature of "record only disasters but not normal conditions" in the historical documents (Zheng et al., 2014), the average recording rates suggest that a significant proportion of drought and flood events were recorded in the HRB from 1426-1950, meeting the ideal proportion of extreme droughts and floods (20%) required for the study.

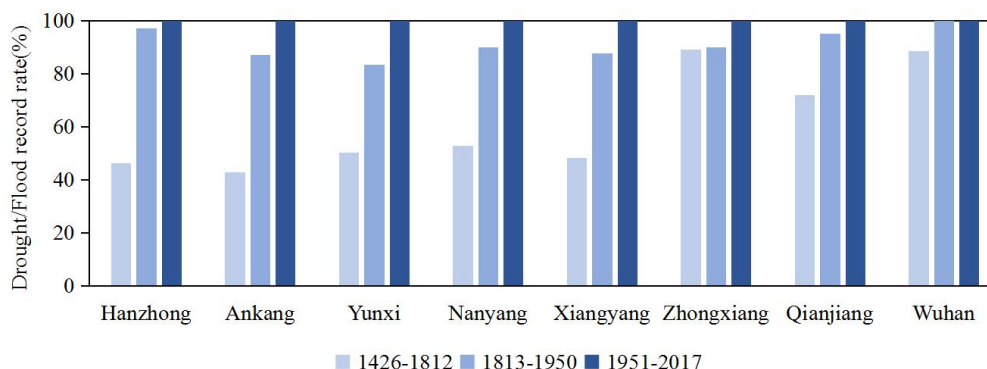



Figure: 2 Proportion of drought and flood records in different periods of various sites

Furthermore, since there were missing data records at each site in historical periods, the more documented periods have richer records of droughts/floods, and vice versa. However, the lack of data should not significantly impact the proportion of droughts/floods in the available drought/flood records. Therefore, the following standards were used to identify extreme drought/flood events in the basin (Hao et al., 2010a): Firstly, the number of sites with a drought or flood grade of 3 (i.e. a normal year) out of the total number of sites recorded in the same year does not exceed 25% of the total number of sites recorded. Secondly, among the sites with records of droughts and floods (i.e. except for sites with a drought/flood grade of 3),

at least 75% of the sites have droughts or floods at the same time, meanwhile, at least 2 of these adjacent sites were experiencing either severe drought (i.e. grade 5 drought) or severe flood (i.e. grade 1 flood) at the same time. If the above two conditions were met, the year could be identified as a year of extreme drought or flood in the basin.

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(2)Chi-square test (χ^2)

The chi-square test is a way of inferring whether the overall distribution is significantly different from the expected distribution or a particular theoretical distribution, based on the current state of the sample distribution. In this study, the correlation between extreme droughts/floods and the occurrence of strong ENSO and large volcanic eruptions was calculated
270   and detected using a chi-square test (χ^2).

3 Results and discussion

3.1 Variation characteristics of extreme drought and flood events

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There were 45 extreme drought events and 51 extreme flood events identified (Table 2) in the period 1426-2017. They account for 7.6% and 8.61% of the total number of years, respectively, equivalent to an extreme drought event per 13 years and an extreme flood event per 12 years. The occurrence probability of extreme flood years is marginally higher than that of extreme drought years. During this period, extreme drought/flood events had prominent phased and clustering characteristics
280   of occurrences. Figure 3 shows the statistical results (frequency) of the extreme drought and flood events per decade, and following features can be generalized:

(1) The high-incidence period of extreme drought events occurred in the 15th to early 16th, 17th, and 20th centuries; both lasted around 100 years. Furthermore, 1441-1442, 1479-1480, 1689-1690, and 1941-1942 were consecutive years of extreme droughts. These continuous extreme drought events have had a more severe impact on agricultural and social life. For
285   example, during 1941-1942, the HRB suffered a summer and autumn drought without rain, and the seedlings withered without harvest, This tremendous northern drought, centred on Henan Province (Dong et al., 2014), not only led to food failures and shortages but also caused millions of refugees to die as a result of the famine (Li, 2019). The 20th century saw the highest incidence of extreme drought events, occurring about once per seven years. There was a severe drought in Northwestern China in 1928, with annual precipitation comparable to that during the Ming Chongzhen drought (Tan, 2003).
290   There were many records in the HRB regarding the drought in 1928, such as: "The sun is harsh in the summer, and the rivers are parched", " The victims had eaten all the bark and grass within hundreds of miles and recently had to dig the soil in the mountains to eat, causing many of them to die from dry stools ", "Last year (1928), a severe drought affected thousands of miles within a radius from spring to summer", etc. However, there were no extreme drought events in the 1460s, 1510s, 1530s, 1550-1660s, 1620-1630s, 1660s, 1700-1750s, 1790-1800s, 1820-1840s, 1860s, 1880-1890s, 1930s and 1980s.

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Table 2: Statistics on historical extreme drought/flood per century, 1426-2017

Century	Extreme drought	Total (year)	Extreme flood	Total (year)
15th (1426-)	1433, 1441, 1442, 1444, 1450, 1458, 1479, 1480, 1485, 1489, 1498	11	1460, 1474	2
16th	1509, 1522, 1528, 1544	4	1500, 1516, 1517, 1519, 1551, 1560, 1566, 1569, 1591, 1593	10
17th	1617, 1644, 1640, 1652, 1674, 1684, 1698, 1690, 1692	9	1607, 1608, 1613, 1631, 1647, 1650, 1653, 1658, 1676, 1677	10

18th	1768, 1778, 1785	3	1724, 1742	2
19th	1813, 1856, 1877	3	1822, 1831, 1832, 1848, 1852, 1870, 1883, 1887, 1889, 1897	10
20th	1900, 1914, 1928, 194, 1942, 1944, 1959, 1961, 1966, 1972, 1976, 1978, 1994, 1999	14	1906, 1909, 1910, 1919, 1921, 1924, 1931, 1933, 1954, 1979, 1980, 1983, 1996, 1998	14
21th (-2017)	2001	1	2000, 2010, 2013	3

300 (2) The high-incidence period of extreme flood events occurred in the 16th to 17th centuries and the 19th to 20th centuries, both lasted around 200 years. Furthermore, 1516-1517, 1607-1608, 1631-1632, 1676-1677, 1831-1832, 1909-1910 and 1979-1980 were consecutive years of extreme floods. The 19th to 20th centuries saw the highest incidence of extreme flood events, occurring about once per eight years. For example, in 1870, an most enormous flood in the Yangtze River Basin in more than 800 years occurred (Yao, 1991), flooding 30,000km^2 of the Jianghan Plain (Shi et al., 2004), including the

305 downstream areas of the HRB. In the extreme flood of 1931, Hankou reached record high water level (28.28m), with a peak flow of 50,000m^3/s at Danjiangkou and 145,000 deaths across the Yangtze River Basin (Shi et al., 2004). Lake Taibai, the largest lake in the Jianghan Plain in the 17th century, was silted up to a low-lying swamp by the end of the 19th century due to the Yangtze and Hanjiang rivers' frequent floods, which led to a sharp increase in sediment (Yao, 1991). However, there were no extreme flood events in the 1430s-1450s, 1480-1490s, 1520-1540s, 1570-1580s, 1620s, 1660s, 1680-1710s, 1730s,

310 1750-1810s, 1860s, 1940s and 1960s.
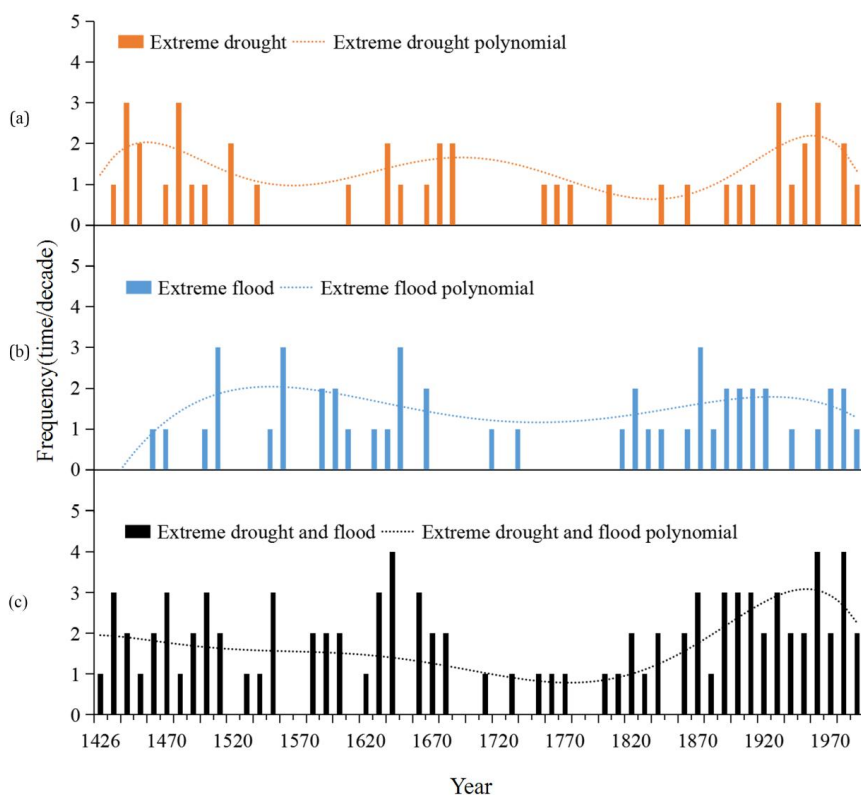
Figure 3: Change in frequency of extreme droughts/floods per decade, 1430-2000 (times/decade). (a) Years of extreme droughts; (b) Years of extreme floods; (c) Years of extreme droughts/floods. The dashed line is the 6th order polynomial fit curve.

(3) The 18th century was a period of relatively few extreme drought/flood events, with 3 extreme drought events, 2 extreme flood events and approximately 1 extreme drought or flood event per two decades. The stalagmite records from Central China and the hydrographic stonework from the Three Gorges area of the Yangtze River also suggested fewer droughts and floods in the 18th century. For example, Liu et al. (2011) used high-resolution stalagmite $\delta^{18}O$ and high-precision ^{230} Th dating data from Wanxiang Cave, Wudu County, and combined with historical drought and flood index series from the surrounding area. They found that 1701-1780 was a stable period for precipitation, with above-average precipitation and no extreme drought or flood events. Qin et al. (2020) analyzed the frequency of severe drought events in the Yangtze River's upper reaches through the hydrographic stone carvings of Baiheliang stonefish in the Three Gorges Reservoir area of the Yangtze River. They found that there were significantly fewer records of extreme drought events in the 18th century. Studies combining ice cores, tree ring index, lake sediments, and historical climate records indicated that the 18th century was a relatively warm period during the Little Ice Age, when temperatures in China began to rise and climatic conditions improved significantly relative to the previous period (Yang et al., 2002).

(4) The 20th century was a common high period of extreme drought/flood events, with 14 extreme droughts and 14 extreme floods occurred, and approximately 1 extreme drought or flood event average 3-4 years. Tree-ring reconstruction studies (Zhang et al., 2005; Liang et al., 2003) indicated that the monsoon precipitation variability in northern China over the last 100 years has been high, with significant wet and dry changes and widespread extreme drought events. Ding et al. (2006)

335 and Ren et al. (2010) pointed out that in the context of global warming, the frequency and intensity of extreme precipitation events and the extent of drought in China increased during the 20th century, especially in the past half-century, the extreme precipitation in Northwest China has increased significantly. However, the drought events in North China, northeast and southwest China have increased significantly. The analysis results of this study are in good agreement with previous research conclusions.

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(5) The frequency of extreme droughts was relatively high in the 20th century, especially after the 1930s. Historically, however, the frequency of extreme drought in the 20th century does not appear to be the highest, with a similar frequency of extreme drought events occurring in the mid-15th century. The decline in the frequency of extreme droughts during the 18th-19th centuries amid the Little Ice Age is equally evident in Figure 3. However, extreme flood frequency appears to have

345 been higher in the 20th century and significantly more frequent than in the 18th and early 19th centuries. This feature of the century-scale variation in the frequency of extreme droughts/floods is also evident in all subsequent analyses of the frequency of extreme drought/flood events per 30-year period (Figure 4).

3.2 Factors influencing the variability of historical extreme droughts and floods

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3.2.1 Asian Monsoon

The Asian monsoon is divided into East Asian monsoon and South Asian monsoon. HRB is located at the junction of Central, North and Northwest China and may be influenced by both East Asian monsoon and South Asian monsoon systems (Su,

355 1981; Yin et al., 2015). Figure 4 shows a visual comparison of extreme drought and flood events with the East Asia-South Asia Summer monsoon Index. Then the following correspondence can be found that:

(1)15th-17th century, the monsoon was generally weak, and extreme drought events were relatively more likely to occurred.

(2)18th-19th century, the monsoon gradually strengthened, and there were more extreme flood events than extreme drought events. Specifically, there were relatively few extreme events in the 18th century and an increase in extreme events in the

360 19th century, with 10 extreme floods and 3 extreme droughts occurred in the 19th century, more than 3 times as many extreme floods as extreme droughts. This phenomenon further illustrates the complexity of the mechanisms by which extreme drought and flood events occur.

(3) The second half of the 19th century and the 20th century saw a monsoon's significant strength and a marked increase in extreme drought and flood events. As revealed by other studies (Huang et al., 1999; Lu, 2002; Niu et al., 2004), in the second

365 half of the 20th century, abrupt changes in global atmospheric circulation and an unusual weakening of the monsoon led to an increase in extreme drought events. Therefore, extreme droughts and floods in the 20th century have broadly evolved through a process of main floods, followed by a shift from floods to droughts, consistent with Ye and Zhao's (1995) analysis of the changing characteristics of droughts/floods in the middle reaches of the Yangtze River.

The correlation analysis of extreme drought and flood grades per 30 years with the East Asian-South Asian summer

370 monsoon strength index per 30 years all passed the significance test of $P<0.01$. Therefore, this suggests that the multi-decadal variation in the frequency of extreme drought/flood events are greatly influenced by changes in the strength of the Asian monsoon, with more prone to extreme drought events when the monsoon is weak and extreme flood events when the monsoon is strong. The water vapour that precipitates most of China originates from the warm and humid air currents brought by the Asian summer monsoon, the strength of which is closely related to precipitation and drought/flood anomalies

375 in China. It can be seen from other studies in the HRB (Yin et al., 2015; Su, 1981) that during the weak East-South Asian monsoon, the rain belt hovers over the Yangtze River and its south, and drought is more likely to occur in the HRB, especially in the upper reaches. Conversely, when during the strong East-South Asian monsoon, the upper HRB is prone to heavy rainfall even floods in summer and to continuous rain or floods in autumn. Moreover, the South Asian monsoon has a greater impact on precipitation in the HRB, when the South Asian monsoon is stronger, the HRB is more prone to floods.

380 This study is in good agreement with the previous conclusions above.

However, precipitation and extreme droughts/floods are also affected by other environmental factors and the complex

interactions between different factors. Meanwhile, there may also be differences in the monsoon's impact on the upper and lower reaches of the Hanjiang River. Therefore, the relationship between historical basin-based extreme droughts/floods in the HRB and the Asian Monsoon Index on era to multi-decade scale is not a one-to-one correspondence.

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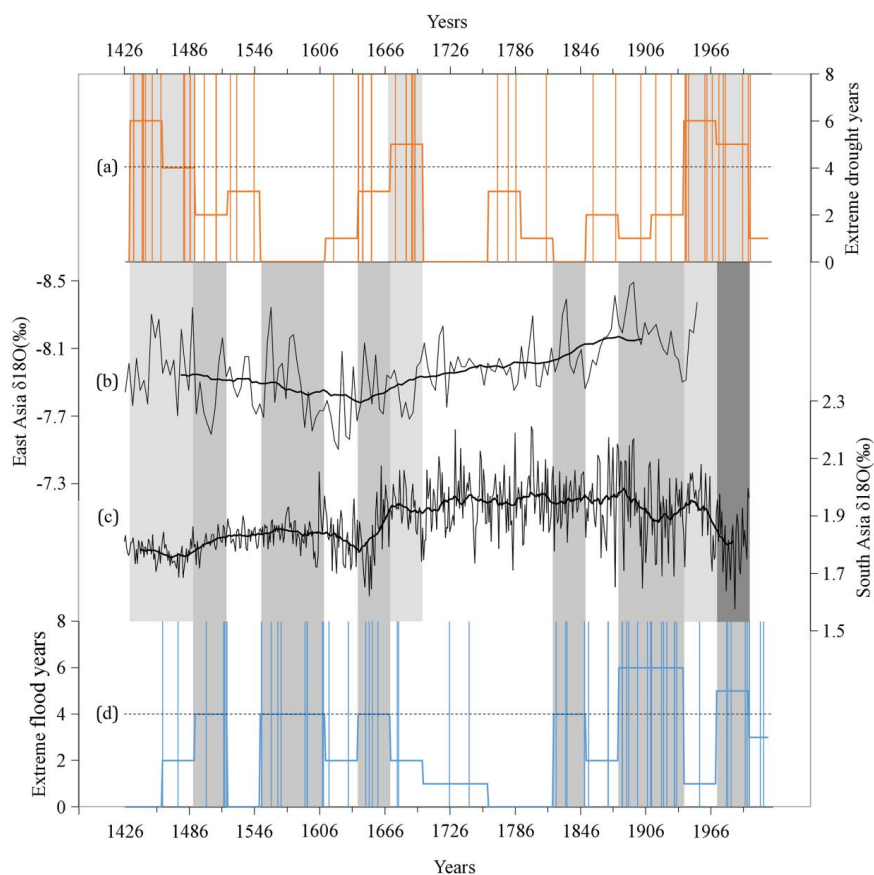
Figure 4: Comparison of extreme drought/flood years with the Asian monsoon index series. (a) The vertical line shows the extreme drought years, and the ladder is the number of extreme drought years per 30 years. (b) East Asian summer monsoon index series, 1426-1949 (Zhang et al., 2008). (c) South Asian summer monsoon index series, 1426-2000 (Shi et al., 2017). (d) The vertical line shows the extreme flood years, and the ladder is the number of extreme flood years per 30 years.

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3.2.2 Strong ENSO events

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ENSO are El Niño and La Niña phenomena that occurred in the equatorial eastern Pacific. Table 3 shows the correlation coefficients between the number of strong ENSO per 30 years and the number of extreme droughts/floods per 30 years from 1525-2002. We found that extreme floods are significantly positively correlated with strong El Niño at a Multi-chronological scale and passed the significance test (Figure 5). However, extreme droughts and strong El Niño/La Niña, extreme floods and strong La Niña also showed positive correlations but did not pass the significance test. Furthermore, a chi-square test for strong ENSO events and extreme drought/flood events per 30 years shows that on an interannual scale, the chi-square values for extreme droughts and El Niño at the 1530s-1550s and 1860s-1880s are 9.310 and 6.724, respectively, passed the

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significance test of P<0.01; and in the 1890s-1910s and 1920s-1940s are 5 and 5.37, respectively, passed the significance test
of P<0.05. The chi-squared value of 6 between extreme floods and EI Niño in the 1590s-1610s passed the significance test of

405   P<0.05, and the chi-squared value of 6.724 between La Niña in the 1740s-1760s passed the significance test of P<0.01.
However, the correlation between extreme droughts/floods and strong ENSO are not significant in the other eras.

Table 3: Correlation coefficients for the number of extreme droughts/floods and strong ENSO per 30 years, 1525-2002

	Extreme drought	Extreme flood
El Niño	0.099	0.593**
La Niña	0.103	0.135

410   ** refers to the correlation is statistically significant at the level of 0.05.

ENSO events, as one of the strong signals of interannual variability in sea-air interactions, have a strong influence on the
strength of the monsoon (Zhao et al., 2000; Wang et al., 2000; Liu and Ding, 1995; Malmgren et al., 2003). In general, EI
Niño caused weakened summer monsoon in East Asia and a southerly position of the paramount front, with a flood in the

415   Jianghuai region and the southern coast of China and drought in northern China. Conversely, La Niña caused an increase in
summer monsoon in East Asia and a northerly position of the paramount front, resulting in most south-central China, except
for the southeast coast, being under the control of the paramount, mainly in the form of heat and little rain (Tao and Zhang,
1995; Liu and Jin, 2015). Yin et al. (2015) studied the relationship between precipitation and ENSO events in the upper
Hanjiang River during 1950-2010. They found that in years with strong EI Niño at the end of the previous year or the

420   beginning of the same year and in years when El Niño switched to La Niña, floods occurred with large high-frequency peaks
in the upper Hanjiang River. Hao et al. (2008) found that in the year or the next year of El Niño, precipitation in the middle
and lower reaches of the Yellow River is lower than usual; the globalised drought phenomenon of 1876-1878 was associated
with the unusual high intensity of the El Niño event (Hao, et al., 2010b). Furthermore, the strongest EI Niño event in the
20th century occurred in 1997-1998, which led to widespread abnormal precipitation in the Jianghuai basin, which was an

425   important factor in the basin-wide significant floods in the Yangtze River in 1998 (Qian et al., 2007; Zhao et al., 2000).
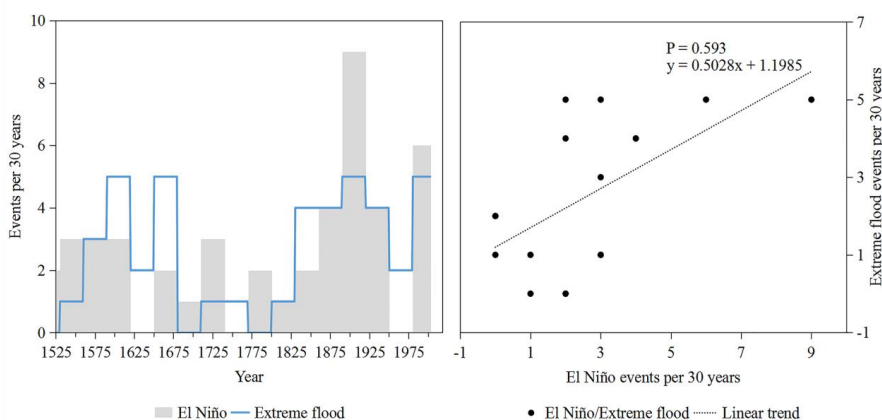
Figure 5: Correlation of extreme flood and strong El Niño per 30 years, 1525-2002.

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The HRB is a transitional zone between northern and southern China and between the subtropical and warm temperate
zones, so it is susceptible to monsoon strength changes. In addition, the Ba shan Mountains to the south and the Qinling
Mountains to the north of the Hanjiang River have a common blocking effect on airflow, allowing the front of subtropical

high pressure to remain in the region for a more extended period, amplifying the effect of the monsoon on precipitation.

435 Therefore, when ENSO events occur, the HRB is vulnerable to both drought and flood conditions. However, due to the lower Hanjiang River's southerly latitude, the response of the El Niño to precipitation in the lower Hanjiang River may be different from that in the upper. This may be why the extreme drought/flood in the whole HRB have no obvious correlation with the El Niño.

3.2.3 Large volcanic eruptions

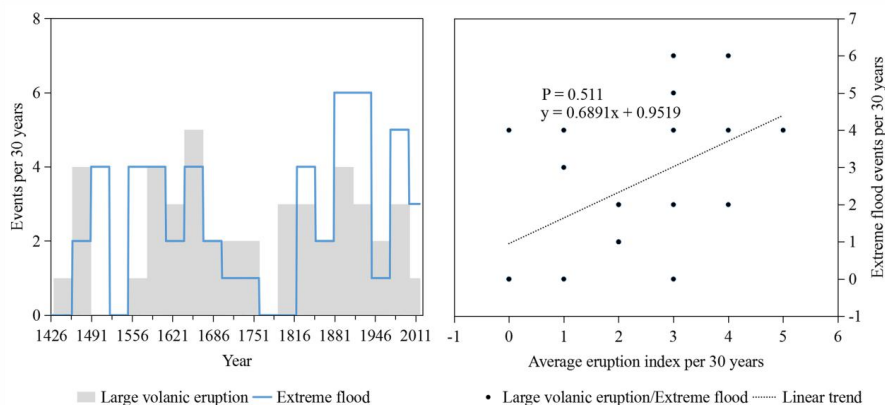
440 The correlation between the number of large volcanic eruptions per 30 years and the number of extreme droughts/floods per 30 years from 1426-2017 was analysed. It is shown that on a multi-year intergenerational scale, the correlation coefficient between large volcanic eruptions and extreme floods was 0.511, which passed the correlation test of $P<0.05$ (Figure 6), but the correlation between extreme droughts was not significant. Furthermore, a chi-square test for extreme 445 drought/flood events and large volcanic eruptions per 30 years shows that on an interannual scale, the chi-square values for extreme droughts and large volcanic eruptions at the 1430s-1450s and 1640s-1660s are 4.138 and 6, respectively, passed the significance test of $P<0.05$. However, the correlation between extreme droughts/floods and large volcanic eruptions are not significant in the other eras.

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Figure 6: Correlation of extreme flood and large volcanic eruptions per 30 years, 1426-2017.

Volcanic eruptions can reduce the global average temperature (Li et al., 1994). Meanwhile, volcanic ash and sulfur 455 dioxide gas produced by volcanic eruptions increase the hygroscopic condensation nuclei in the atmosphere, which has a catalytic effect on the occurrence and intensification of precipitation (Mann et al., 1998; Liu et al., 2016). Moreover, the aerosols formed during the eruption affect solar radiation, indirectly changing atmospheric circulation, thereby causing precipitation and distribution changes. Zhang and Zhang (1994) studied the statistical relationship between large volcanic eruptions in 8 global regions and droughts/floods in China since the 15th century. They found that large volcanic eruptions at 460 different latitudes worldwide have different effects on droughts/floods in different China regions. After large volcanic eruptions in the Kamchatka Peninsula-Ryukyu Islands and Alaska-San Francisco areas, the middle and lower reaches of the Yangtze River towards rain and floods. Conversely, the large volcanic eruptions in Mexico-Peru and Vanuatu-New Zealand led to drought in the middle and lower reaches of the Yangtze River. Zhang et al.(2020) investigated the impact of the Indonesia-Philippines large volcanic eruptions from 1500 to 2000 on the drought/flood pattern in central and eastern China. 465 They found that North and South China changed from drought to flood and from flood to drought after the large volcanic eruptions, which lasted about 2-3 years. In 1980, the Yangtze River Basin experienced constant summer rainfall and shallow temperature, while northern China and Inner Mongolia experienced a rare drought, which some studies suggest may be related to the eruption of the St. Helens volcano in May 1980 (Zhou, 1981; Xu, 1986).

Large volcanic activity is an important natural driver of climate change and can impact global and regional temperature
470 and precipitation changes. However, the relationship between volcanic activity and climate change is complex. It requires a
combination of factors such as the intensity of the eruption, the season and geographical location, etc. Therefore, it is
difficult to separate the effects of volcanic activity from the various influencing factors, so there are no systematic studies to
date to distinguish the effects of volcanic activity from precipitation data (Huang et al., 1998; Zhang and Zhang, 1985).

475 **4 Conclusions**

This study investigated the era to multi-decade scale variation of extreme drought and flood over Hanjiang River Basin
based on the 8-site precipitation grade reconstruction for 1426-2017. The main conclusions are as follows:
1) A total of 45 extreme drought events and 51 extreme flood events occurred from 1426-2017, equivalent to an extreme
480 drought event per 13 years and an extreme flood event per 12 years. Extreme flood events occurred slightly more frequently
than extreme drought events.
2) The relatively frequent periods of extreme drought events occurred in the 15th century to the early 16th century, the 17th
century, and the 20th century. The highest frequency of extreme drought events occurred in the 20th century, while the 18th
century saw the lowest frequency of extreme drought events.
485 3) The relatively frequent periods of extreme flood events occurred in the 16th to 17th centuries and the 19th to 20th
centuries. The highest frequency of extreme flood events occurred in the 19th and 20th centuries, while the 18th century saw
the lowest frequency of extreme flood events.
4) The frequency of both extreme drought and flood events was low in the 18th century, and there were probably fewer
droughts and floods. However, the 20th century saw a high frequency of both extreme drought and flood events and an
490 increased risk of drought and flood disasters.
5) Extreme droughts in the Hanjiang River Basin are more likely to occur when the Asian monsoon is weak. Conversely, the
Hanjiang River Basin is more prone to extreme floods when the Asian monsoon is strong.
6) ENSO and large volcanic eruptions may also influence the occurrence of extreme droughts and floods. On a
multi-decadal scale, extreme floods show an increasing trend with El Niño and large volcanic eruptions.
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Data availability. All reconstructed data for the identification of extreme drought and flood events used in this study are
500 available in the Supplement. Dataset of East Asian summer monsoon are available at
https://www.ncdc.noaa.gov/paleo/study/8629 (NOAA, 2008) and South Asian summer monsoon are available at
http://www.ncdc.noaa.gov/paleo/study/17369 (NOAA, 2014). Chronology of El Niño and La Niña events are available at
https://www.ncdc.noaa.gov/paleo-search/study/8408 (NOAA, 2018). The "China National Ground Meteorological Station
Homogenized Precipitation Data Set (V1.0)" is non-public.
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Author contributions. GR and BH designed the research programme and guided the writing throughout; YY and ZH guided
ideas for writing; PZ guided the technical part; XZ reconstructed the precipitation series, analysed the data, plotted and
wrote.
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Competing interests. The authors declare that they have no conflict of interest.

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