Extreme historical droughts and floods in the Hanjiang River basin, China, since 1426

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Abstract: The major droughts and floods in the Hanjiang River basin, central China, 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. However, there is a lack of understanding of the multi-decadal to centennial-scale patterns of extreme droughts and floods in the area. Applying the yearly drought/flood records from historical documents and precipitation data in the period of instrumental measurements, this study constructs a time series of extreme droughts and floods in the Hanjiang River basin from 1426–2017, and analyzes the temporal and spatial characteristics of the extreme drought/flood events variations. The results show that there were total 45 extreme droughts and 52 extreme floods in the basin over the past 592 years. Extreme droughts and floods were highly variable on multi-decadal to centennial-scale, and the frequencies were higher in the first and last one hundred years or so of the study period and lower in between. Spatially, the frequencies of extreme droughts and floods were generally higher in the middle and lower reaches than in the upper reaches. It was also found that there is a good correlation of droughts and floods frequencies between the upper Hanjiang River basin and North China. These results are informative for the study of mechanisms and predictability of multi-decadal to centennial-scale variability of extreme hydro-climatic events in the river basin.

Key words: Drought; Flood; Climate variation; Historical documents; Hanjiang River; Yangtze River

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 tremendous impact on the society and economy.

Global climate warming has been affirmed in academic circles and the global surface temperature increase in the 21st century will probably exceed 1.5-2.5℃ (IPCC, 2013). The climate warming not only directly affects changes in temperature extremes but also lead to changes in the frequency of regional droughts and floods (Goswami et al., 2006; Krysanova et al., 2008; Dai, 2013; Aiken and Rauscher, 2019). The IPCC Sixth Assessment Report (AR6) states that 3–4 billion people globally would face physical water scarcity under 2.0℃ and 4.0℃ warming scenarios (IPCC, 2021). Furthermore, the risk of floods will double when the globe warms between 1.5℃ and 3.0℃, and economic, agricultural, and potential hydropower losses will increase as warming increases further (IPCC, 2021). Observational studies have shown an increasing trend in precipitation over much of the mid to high latitudes during 1901–2010. However, decreasing trends of precipitation have been observed in other regions including northern Africa, the Mediterranean, southern Africa, and much of eastern and southern Asia (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 North China, Southwest China and southern Northeast 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., 2008a; Chen et al., 2012; 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, that in North China and southwestern Northeast China beginning to increase, and the drought in Southwest China intensified (Ren et al., 2015a; 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, and 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 projecting future climate. Therefore, the long-term observations or proxy data of the past hundred to several hundred years at different spatial scales are first required to meet the demand of the studies.

In most parts of the world, including 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 (Mikami, 2008; Cook et al., 2010; Machado et al., 2011; IPCC, 2012, 2013; Fenby and Gergis, 2013; Shi et al., 2018, 2019).

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 (e.g. Zhao and Wang, 1979; Zhang and Gong, 1979; Central Meteorological Bureau, 1981; Zhang, 1989; Hao et al., 2010; Han and Yang, 2017; Zheng et al., 2020). These studies laid a good foundation for further investigating into the multi-decadal to centennial scale variability of historical droughts and floods in the country. However, most of the above studies only 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., 2015b). 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 big spatial differences in precipitation and drought/flood events in historical periods. In the climatic transition zones, the spatial characteristics of climate change and variability are more complex (Zheng et al., 1993; Liu et al., 2010; Wan et al., 2018; Mei et al., 2019).

The Hanjiang River is one of the major tributaries of the Yangtze River. Located in the northern subtropical climate zone to the south of the Qinling Mountains, and in the transition zone between China's northern and southern climates, the Hanjiang River Basin (HRB) is sensitive to climate and environmental change (Zhu, 1958; Miao et al., 2009). On the other hand, 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 (Liu et al., 2018; Wang et al., 2021). Therefore, there is an urgent need for research on precipitation and drought/flood variability at the multi-decadal to centennial scales in the HRB.

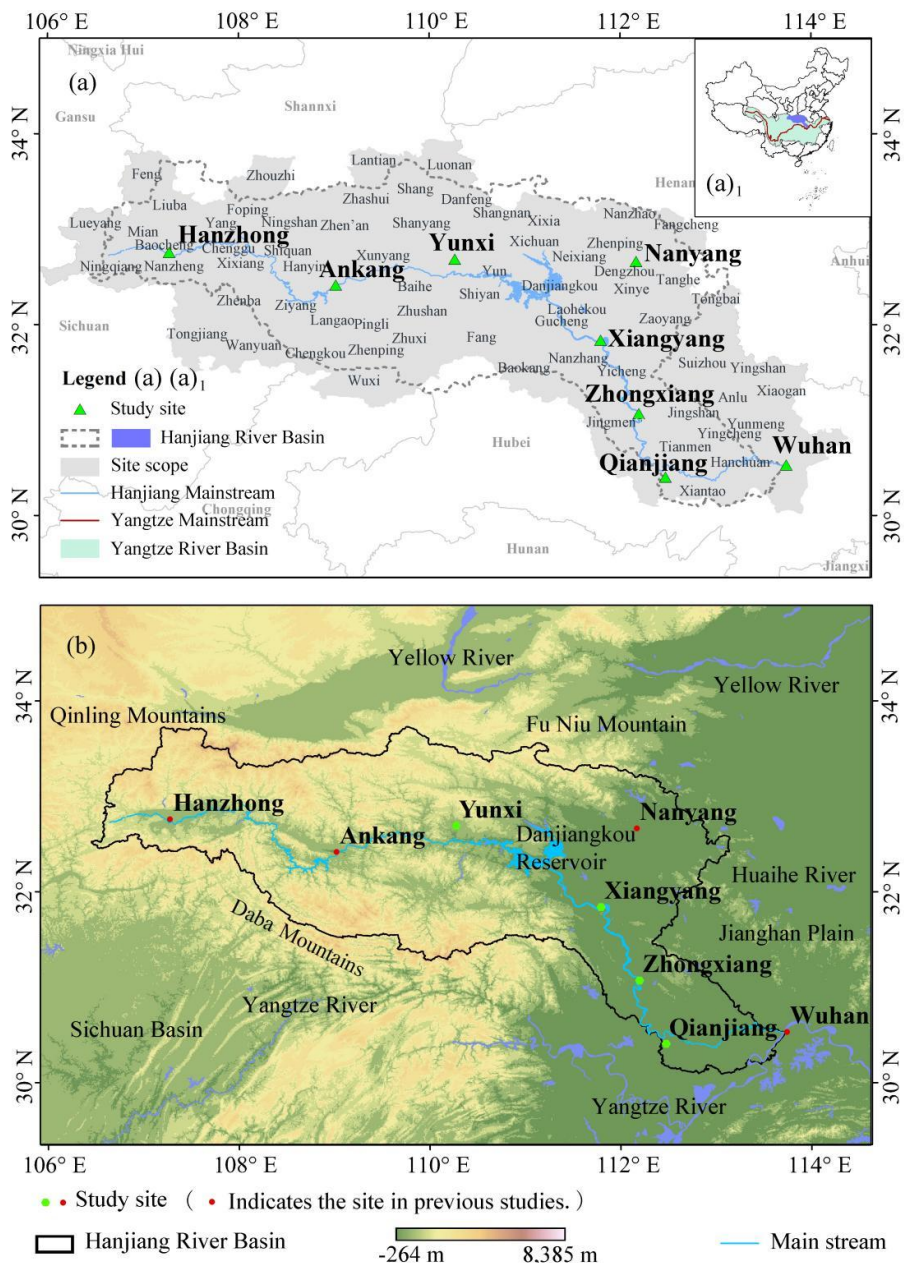
There were a few of previous studies on the HRB's historical precipitation, but most of them were focused on the upper Hanjiang River region (Yin et al., 2010; Yin et al., 2013; Huang et al., 2013; Peng et al., 2013; Zhou et al., 2014; Yin, 2015; Mao et al., 2016; Zhou et al., 2016; Tan et al., 2018); there were relatively few relevant studies on the entire basin (Zhou et al., 2006; Ding and Zheng, 2020). An in-depth understanding of the multi-decadal to centennial scale variability of historical drought/flood thus is lacking. 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 HRB from 1426 to 2017. The results presented in the paper would be helpful for understanding the multi-decadal to centennial 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, and an average annual

precipitation of 700–1300mm (1960–2010) (Yin, 2015). HRB has a humid subtropical monsoon climate with a pronounced spatial difference of 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 (above the Danjiangkou Dam) 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 (Danjiangkou to Zhongxiang is the midstream and below Zhongxiang is the downstream) 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, resulting in frequent floods (Institute of Geography of Chinese Academy of Sciences, 1957). Since the early 1990s, the HRB as a whole has tended towards more frequent droughts, which severely impacted the ecological environment, the rational allocation of water resources and the water supply in the basin (Chen et al., 2006; Wang and Guo, 2010; Yin, 2015).

145 **Figure 1: Study area and locations of the eight prefecture capitals used for reconstruction of drought and flood (a, a₁, b). The green points in (b) represent the sites first reconstructed in this study, and study sites in previous work (Central Meteorological Bureau, 1981) are marked as red points in (b). The inset (a)₁ in (a) indicates the relative location of the study area in China.**

150 **2.2 Data**

Four datasets were used in this work. These include the historical drought and flood records of the HRB (this study), the drought and flood index series in North China (the Yellow River and the North China Plain, 1470–2000), the Asian Monsoon Index series, and the chronologies of strong ENSO
155 events.

(1) Historical drought and flood data series and documentation

The information used in this study to reconstruct the drought and flood sequences was divided into two parts: historical data and instrumental data. Sources of historical data included local chronicles,
160 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 BC to 1911 AD. In addition, other datasets were also collected and used, including "The Historical Documents on Flood and Waterlogging of Southwest International
165 Rivers in the Yangtze River Basin in Qing Dynasty (1636–1912 AD)″ (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,
170 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 Meteorological Disaster Dictionary" (Shaanxi Volume, Henan Volume, Hubei Volume; Wen, 2005, 2005, 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
175 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 (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.

180 The instrumental data (started in 1951) comes from the monthly precipitation dataset "China National Ground Meteorological Station Homogenized Precipitation Data Set (V1.0)" (Yang and Li, 2014). This set of precipitation observations were quality controlled, and tested and adjusted for inhomogeneity caused by non-climatic factors such as the relocation of stations and instrumentation. This study uses precipitation data from 8 meteorological stations (Hanzhong, Ankang, Yunxi, Nanyang,
185 Xiangyang, Zhongxiang, Qianjiang and Wuhan) in the HRB (Figure 1).

(2) Other historical data series

Drought and flood index series in North China (the Yellow River and the North China Plain,

1470–2000) were used to compare the result of this analysis with those of other regions. The data were from "The Atlas of Drought and Flood Distribution in China in the Last 500 Years" (hereafter referred to as Atlas; Central Meteorological Bureau, 1981), and the drought and flood grades of North China were read out from the Atlas.

Asian monsoon index. The East Asian summer monsoon index dataset (1426–1949) reconstructed by Zhang et al. (2008b) was used in this study. They conducted a climate reconstruction of East Asian summer monsoon strength based on accurate dating by using high-resolution stalagmite $\delta^{18}O$ series of Wanxiang Cave in Wudu (33°N, 104°E), Gansu province. Moreover, the updated South Asian summer monsoon index dataset (1426–2000) by Shi et al. (2017) was also used. This dataset used eight additional Indian tree-ring width chronologies from the South Asian summer monsoon core region to update the earlier reconstruction by Shi et al. (2014).

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 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.

2.3 Methods

(1) Reconstruction method of historical drought and flood grade

Based on the criteria provided in the Atlas, 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 administrative range (i.e. including several counties and cities) 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 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 droughts and floods occurred successively at the same site in the same year, for instance, spring droughts and summer floods, or summer droughts and autumn floods, etc., the summer condition was considered prevailing. If there were droughts and floods within the representative area (i.e. the site), the judgment would be based on most counties or cities' 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 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. Moreover, 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 (Central Meteorological Bureau, 1981). Table 1 shows the division criteria in the HRB into various grades and their typical descriptions in historical sources (the criteria for judging the historical sources according to the Atlas) and the criteria for grading precipitation (Central

Meteorological Bureau, 1981).

Table 1: Criteria for classifying droughts and floods in the HRB 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.	$R_i > (\bar{R} + 1.17\sigma)$
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.	$(\bar{R} + 0.33\sigma) < R_i \leq (\bar{R} + 1.17\sigma)$
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.	$(\bar{R} - 1.17\sigma) < R_i \leq (\bar{R} - 0.33\sigma)$
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.	$R_i \leq (\bar{R} - 1.17\sigma)$

R_i **means May–September precipitation in a year,** $\bar{R}$ **means May–September average precipitation in a reference period, σ means standard deviation.**

Based on the above methods and 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 abundance of historical data, a total of eight sites were determined for constructing drought/flood grade

series. These sites are Hanzhong, Ankang, Yunxi, Nanyang, Xiangyang, Zhongxiang, Qianjiang, and Wuhan, which also possess the stations of modern meteorological observation, within the HRB (Figure 1). Among them, four were ever used in the Atlas, but the data have been renewed with additional records from the documents. The grade data of the four new sites were completely developed in this study. The name of each site is the name of the county and municipality. However, the drought and flood the site represents were not limited to the administrative area to which its name refers and encompassed a particular geographical area around it (Table 2).

Table 2: Eight sites of drought and flood grade sequence and the spatial ranges (regions) they represented in the HRB during 1426–1950.

Site	Regions
Hanzhong	Hanzhong, Mian, Chenggu, Nanzheng, Baocheng, Liuba, Yang, Ningqiang, Lueyang, Foping, Zhouzhi, Zhen'an, Zhashui, Feng, Ningshan
Ankang	Ankang, Xunyang, Langao, Zhenping, Pingli, Zhuxi, Chengkou, Wuxi, Zhenba, Ziyang, Tongjiang, Shiquan, Xixiang, Hanyin, Wanyuan
Yunxi	Yunxi, Baihe, Shanyang, Shang, Luonan, Lantian, Shangnan, Danfeng, Fang, Zhushan, Baokang
Nanyang	Nanyang, Nanzhao, Dengzhou, Yun, Zhenping, Tanghe, Xixia, Fangcheng, Neixiang, Xichuan, Shiyan
Xiangyang	Xiangyang, Xinye, Nanzhang, Zaoyang, Tongbai, Laohekou, Danjiangkou, Gucheng
Zhongxiang	Zhongxiang, Yicheng, Jingmen, Xiaogan, Anlu, Yunmeng, Suizhou, Yingshan
Qianjiang	Qianjiang, Xiantao, Tianmen, Jingshan
Wuhan	Wuhan, Hanchuan, Yingcheng

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 before 1951 in the study area with reference to the method reported in Yang and Han (2014). On this basis, the homogeneity test of the number of available data at 95% confidence level was performed to determine whether there were systematic biases in the available records. It was revealed that there was 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. The whole period of 1426–2017 were thus divided into three time stages: 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).

275   The key to this method is a phased evaluation approach, which constructs a platform for comparison between historical periods, and historical and instrumental data. That is, because of the nature of "concerning 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. Even in the period when the average rate of data recording at a 280   single site was lowest (42.6% for Ankang during 1426–1812), it was greater than 20% (i. e., the ideal frequency of extreme droughts and floods) and therefore still met the needs of the study.

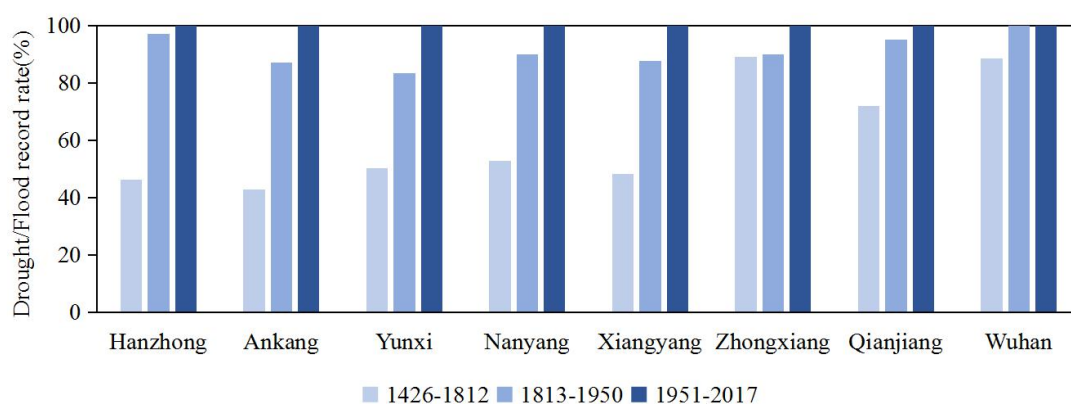



Figure 2: Proportion of drought and flood records in different periods of various sites

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Precipitation anomaly percentages were calculated for May–September of 1951–2017. The method is [annual May–September precipitation‑average May–September precipitation] / average May–September precipitation (both annual and average May–September precipitation is calculated based on precipitation data for each site from May–September for 1951–2017, and average 290   May–September precipitation is the mean of annual May–September accumulated precipitation in the whole period). The precipitation anomaly percentages at the eight sites were then averaged to give the basin-averaged precipitation anomaly percentages for the HRB. Figure 3 shows a comparison of the drought and flood grades established in this study and the precipitation anomaly percentages during the period of 1951-2017. The drought and flood grades and the precipitation anomaly percentages were 295   highly consistent on inter-annual to decadal scale variability, and their correlation passed the 0.01 significance test. Therefore, the drought and flood grades of the instrumental measurement period calculated using the method in the Atlas are able to well indicate the precipitation change, and they can be directly connected with the drought and flood grades of the historical period for use in the following analysis. The applicability of the procedure was also confirmed in previous studies (Wang and Zhao, 300   1979; Fang et al., 2014).
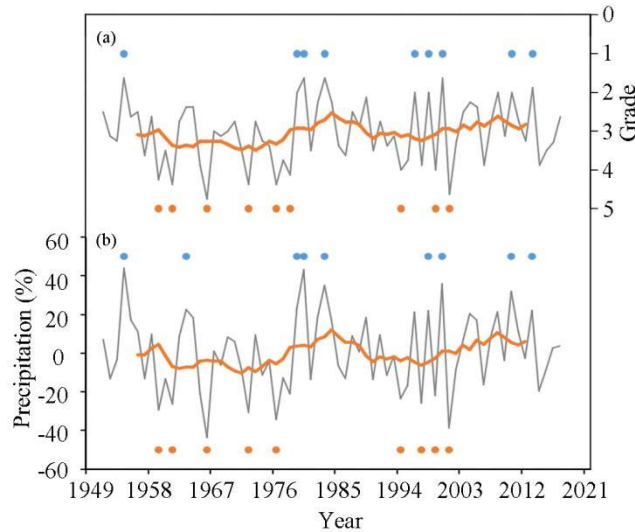
Figure 3: The comparison of drought and flood grades (a) and precipitation anomaly percentage (b) in the HRB during 1951–2017. Blue dots indicate extreme flood years and orange dots indicate extreme drought years.

In addition, there were missing data records at each site in historical periods, and the more documented periods usually have richer records of droughts/floods, and vice versa. However, the lack of data would 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., 2010): 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.

(2) Inverse Distance Weighted (IDW)

The Inverse Distance Weighted (IDW) is a weighted average using the distance between the interpolation point and the sample point as parameter. The closer the sample point to the interpolation point, the greater the weight given. Xie et al. (2018) used four spatial interpolation methods with the Upper Sangamon basin and analyzed the accuracy of the interpolation results separately. They found that IDW had the highest interpolation accuracy when the study area was small and the number of meteorological observation stations was relatively small (Nine sites of observational stations in their analysis; Xie et al., 2018). In this study, we used ArcGIS10.6 with the IDW built-in to map the data of the study sites and to visualize the spatial variability of the droughts and floods grades (Vicente-Serrano et al., 2003; Xie et al., 2018).

3 Results

3.1 Variation characteristics of extreme drought and flood events

335   There were 45 extreme drought events and 52 extreme flood events identified in the period 1426–2017 (Table 3). They account for 7.6% and 8.8% of the total number of years, respectively, equivalent to an extreme drought event per 13 years and an extreme flood event per 11 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 of 340   occurrences. Figure 4 shows the statistical results (frequency) of the extreme drought and flood events per decade (1430–2009), and following features can be generalized.

Table 3: 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, 1640, 1644, 1652, 1674, 1684, 1689, 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, 1941, 1942, 1944, 1959, 1961, 1966, 1972, 1976, 1978, 1994, 1999	14	1906, 1909, 1910, 1919, 1921, 1924, 1931, 1933, 1935, 1954, 1979, 1980, 1983, 1996, 1998	15
21st (–2017)	2001	1	2000, 2010, 2013	3

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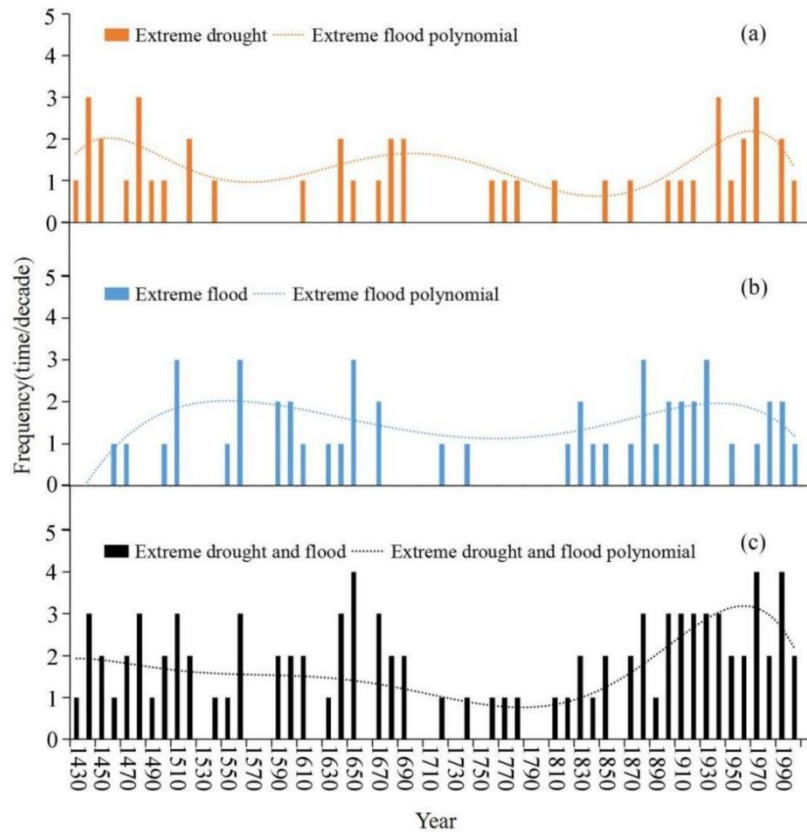
Figure 4: Change in frequency of extreme droughts/floods during 1430–2009 (times/decade). (a) Years of extreme droughts; (b) Years of extreme floods; (c) Years of extreme droughts/floods. The dotted line is the 6th order polynomial fit curve.

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(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. Previous studies showed that the frequency of drought disasters in the HRB was highest in the 1480s and 1630s (Wang and Guo, 2010); 1628–1641 and 1900–1970 were the two periods of the high occurrence of mega-drought disasters in the upper HRB,

355   occurring once every 1.67 years and 3.33 years respectively on average (Yin, 2015). Furthermore, 1441–1442, 1479–1480, 1689–1690, and 1941–1942 were consecutive years of extreme droughts. These continuous extreme events have had a more severe impact on agricultural and social life. For example, during 1941–1942, the HRB suffered an extremely rare successive years of summer and autumn drought without any soaking rain, and the seedlings withered without harvest. This tremendous

360   northern drought, centred on Henan Province (Dong et al., 2014), not only led to crop failures and food 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 eastern Northwest China in 1928, with annual precipitation comparable to that during the Ming Chongzhen drought (the extreme drought that occurred from

365   1637–1643 affected more than 20 provinces in northern China; Tan, 2003). 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" (Wen, Shaanxi Volume, 2005); "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" (Wen, Henan Volume, 2005); and "Last year (1928), a severe drought affected a vast area within

370 a thousand li (ancient Chinese length unit, equivalent to 0.5km) radius from spring to summer" (Wen, Hubei Volume, 2007). The upper reaches of the Danjiangkou Reservoir (completed in 1973, and it is now the water source of the South-North Water Diversion Middle Line Project) had been in drought for years during the late 20th century, especially since the mid-1990s, and the average annual precipitation in the 1990s were 11.6% less than the climatological mean (Chen et al., 2006); in 1997, the HRB was

375 in continuous drought in summer and autumn, and the annual precipitation was only 605mm (Wang and Guo, 2010).

However, there were no extreme drought events in some of the historical periods. These years included the 1460s, 1510s, 1530s, 1550–1600s, 1620–1630s, 1660s, 1700–1750s, 1790–1800s, 1820–1840s, 1860s, 1880–1890s, 1930s and 1980s. In these periods, the HRB experienced relatively

380 normal climate condition or extreme rainstorms and floods.

(2) The high-incidence periods of extreme flood events occurred in the 16th to 17th centuries and the 19th to 20th centuries, both lasted around 200 years. The 19th to 20th centuries saw the highest incidence of extreme flood events, occurring once per eight years. The recently more frequent extreme floods have been reported in previous studies. Yin and Huang (2012) showed that severe floods with flow

385 rates greater than 15,000 m^3/s occurred 20 times in the Ankang area only from 1960 to 2010. They also found the highest frequency of floods occurred in the 1980s, when there were eight severe floods occurred in Ankang, with the maximum flood flow reaching 31,000 m^3/s. In particular, the worst flood in the last 100 years (once in 130 years) occurred in Ankang in July 1983, which caused the inundation of the entire city of Ankang and nearly 1,000 people died (Shaanxi Province local history codification

390 committee, 2000). From 1822 to 1955, there were 130 breaches of the mainstream embankments during 73 years in the middle and lower reaches of the HRB, with an average of about one breach in two years (Guo et al., 2020). In 1870, an most enormous flood in the Yangtze River Basin in more than 800 years occurred (Yao, 1991), flooding 30,000km² of the Jianghan Plain (Shi et al., 2004), including the downstream areas of the HRB. In the extreme flood of 1931, Hankou (Wuhan) registered record

395 (1840–2000) high water level (28.3m), with a peak flow of 50,000m³/s at Danjiangkou and 145,000 deaths across the Yangtze River Basin (Shi et al., 2004).

During the first high-incidence period of extreme floods, the extreme rainstorms and floods events occurred once every 10 years, a little bit less frequent than those in the second period of extreme floods, but still more frequent than other historical periods. Previous studies showed that, after 1550, the

400 climate in the Yangtze River basin was very wet, and there were many severe floods in the following 70 years (Ge, 2011). For example, in 1560, there was a basin-wide extreme flood in the Yangtze River basin second only to 1870 (Ge, 2011). The HRB was seriously affected, and there were many records of this floods, such as "There was a severe flood and access to the city was only possible by boat from August onwards, a situation that lasted until winter" (Zhang, 2004); "There was a severe flood and

405 many people and livestock were drowned" (Zhang, 2004), and so on. During the Northern Wei Dynasty (386–534), Lake Taibai (currently located in Xiantao, Hubei province) was formed by the convergence of tributaries of the Hanjiang River and became the largest lake in the Jianghan Plain in the 16–17th centuries. However, it soon began to be silted up probably mainly due to the Yangtze and Hanjiang rivers' frequent floods and human activities, which led to a sharp increase in sediment, finally

410 becoming a low-lying swamp by the end of the 19th century (Yao, 1991).

There were consecutive years of extreme floods in the history, which should lead to more severe disasters in the basin. These includes the years of 1516–1517, 1607–1608, 1676–1677, 1831–1832, 1909–1910 and 1979–1980. However, there were no extreme flood events in the years of 1430s–1450s,

1480–1490s, 1520–1540s, 1570–1580s, 1620s, 1660s, 1680–1710s, 1730s, 1750–1810s, 1860s, 1940s
415   and 1960s.

(3) The 18th century was a period of relatively few extreme drought/flood events, with three extreme drought events, two extreme flood events and approximately one extreme drought or flood event per two decades. The sparsity of extreme droughts and floods in this century was reported in a previous study applying historical documents (Wang and Guo, 2010). The stalagmite records from Central China
420   and the hydrographic stone inscription from the Three Gorges area of the Yangtze River also suggested fewer droughts and floods in the 18th century (Qin et al., 2020). Liu et al. (2011) applied the high-resolution stalagmite $\delta^{18}O$ and high-precision ^{230}Th dating data from Wanxiang Cave, Wudu County (33°N, 104°E), combined with historical drought and flood index series from the surrounding area, to examine the precipitation variation of the last 500 years at the fringe belt of summer monsoon.
425   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 inscriptions of Baiheliang stonefish in the Three Gorges Reservoir area (31°N, 109°E) of the Yangtze River. They found that there were significantly fewer records of extreme drought events in the 18th century. Studies combining ice
430   cores, tree rings, lake sediments and historical climate records indicated that the 18th century was a relatively warm period during the Little Ice Age, when annual mean temperatures in China began to slightly rise and climatic conditions improved significantly relative to the previous period (Yang et al., 2002).

(4) The 20th century was a common period of high-frequent extreme drought/flood events, with 14
435   extreme droughts and 15 extreme floods occurred, and approximately 1 extreme drought or flood event every 3–4 years. Previous studies showed that annual precipitation in the Hanjiang River basin had decreased since 1960, and drought disasters had increased. At the same time, flood disasters had become more frequent because precipitation was more concentrated in the summer, and inter-annual fluctuations in precipitation had also increased significantly (Yin et al., 2010). For example, floods
440   occurred in the Tangbai River basin, a tributary of the HRB, in 1919 and 1953, but the floods were followed by two months of no rain and then a severe drought (Institute of Geography of Chinese Academy of Sciences, 1957). Tree-ring reconstruction studies (Liang et al., 2003; Zhang et al., 2005) 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. (2007)
445   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, and especially in the past half-century, the extreme precipitation in Northwest and Central China has increased significantly. However, the drought events in North, Northeast and Southwest China have also increased significantly in frequency and severity. The analysis results of this study are in good
450   agreement with the previous research conclusions, but at the same time show the uniqueness of the 20th extreme precipitation change in the history of the last centuries.

(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 did not appear to be the highest, with a similar frequency of extreme drought events also occurring in the mid-15th century.
455   The decline in the frequency of extreme droughts during the 18th –19th centuries amid the Little Ice Age is equally evident in Figure 4. However, the extreme flood frequency appears to have been higher in the 20th century and significantly more frequent than in the 17th and 19th centuries when the HRB also

underwent high frequency of extreme flood events.

3.2 Spatial characteristics of historical extreme droughts and floods

Frequency of Grade 1 floods and Grade 5 droughts at each site was shown in Table 4, and the distributions of frequency were plotted as scatterplot using ArcGIS 10.6 in Figure 5. The spatial patterns of the frequency of the extreme droughts and floods in the HRB varied significantly. The high-frequency centers of extreme floods and extreme droughts are both distributed in the middle and lower reaches of the HRB. Zhongxiang site in the middle reaches of the HRB had a total of 60 extreme droughts, while those at the Nanyang site are relatively less frequent, with a total of 30. The Qianjiang site in the lower reaches of the HRB had a total of 67 extreme floods, and the Ankang site, which is in the upper reaches, experienced relatively fewer extreme floods (40). The frequency of both extreme floods and extreme droughts is generally higher in the middle and lower reaches than that in the upper reaches.

Table 4: The counts of extreme (Grade 5) droughts and extreme (Grade 1) floods at each site in the HRB during 1426–2017

Site	Frequency (extreme drought/extreme flood)	Site	Frequency (extreme drought/extreme flood)
Hanzhong	32/44	Xiangyang	36/44
Ankang	36/40	Zhongxiang	60/58
Yunxi	30/44	Qianjiang	39/67
Nanyang	32/47	Wuhan	44/62

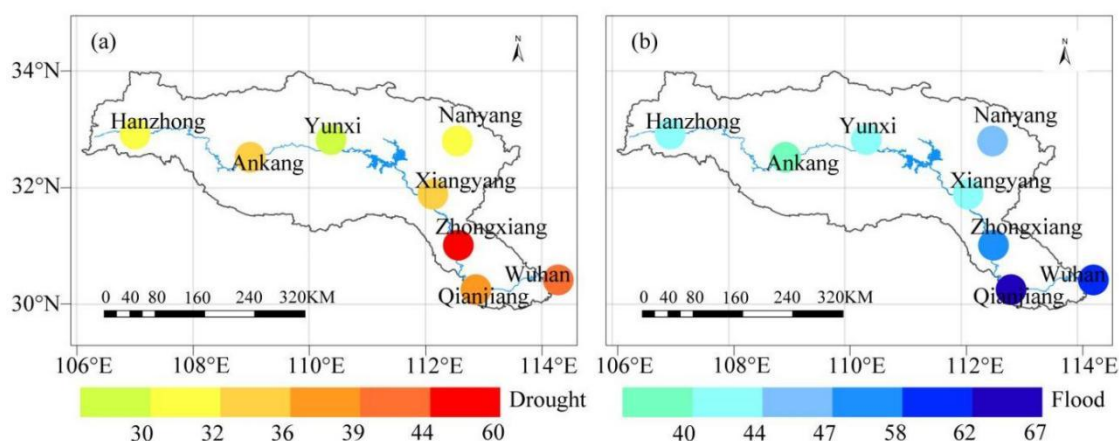



Figure 5: Spatial distribution of the total years of extreme (Grade 5) droughts (a) and extreme (Grade 1) floods (b) in the HRB during 1426–2017.

According to the previous studies (Institute of Geography of Chinese Academy of Sciences, 1957; Commission Water Resources Commission of the Ministry of Water Resources, 2002), the upper reaches of the HRB are more water-scarce and relatively less resistant to drought than the middle and lower reaches. However, the frequency of drought is the highest in the hilly and mountainous areas in the middle reaches of the HRB. That is because the the hilly and mountainous areas in the middle

485   reaches have high arable land, but relatively low ground water table and river flow, and also fewer springs, so in the event of drought, the damage is more serious (Institute of Geography of Chinese Academy of Sciences, 1957). That may be the reason why the drought near the Zhongxiang site in the historical period is relatively more abundantly documented. From Figure 5, it can also be seen that the frequency of droughts and floods is both higher in the middle and lower HRB and plain areas, and
490   lower in the mountainous areas in the upper HRB. This is probably because the middle and lower reaches of the HRB were economically developed earlier, with a more concentrated population and arable land than in the upper reaches. During the Ming and Qing dynasties (1368–1912), the middle reaches of the Yangtze River Plain (including the Jianghan Plain) centered on Hubei Province and Hunan Province had been developed into a national commodity grain supply base. The central
495   government paid as much attention to these areas (Zhu, 2018; Lu, 2019), so the lower reaches of the HRB had documental records in more quantity and detail during the historical period relative to the upper reaches (Figure 2), which may have an influence on the statistical results (Zheng et al., 2014).

    Furthermore, the sensitivity of different regions to droughts and floods cannot be ignored. The severest droughts and floods years in the HRB were identified for each of the 15th –20th centuries
500   (1426–1999), respectively. The years of the severest floods in each century are 1474, 1516, 1647, 1742, 1889, and 1931; the years of the severest droughts in each century are 1433, 1528, 1690, 1768, 1877, and 1928. The average drought and flood grades for each site in the above years were calculated separately and spatially interpolated using the IDW. Each site's drought and flood grades were then plotted using ArcGIS10.6 (Figure 6, Figure 7). It was found that the sites of Ankang, Nanyang, and
505   Qianjiang were relatively more likely to be affected by severe drought, while those of Ankang, Xiangyang, and Zhongxiang were relatively more likely to suffer from severe flood. In particular, the sensitivity of the Ankang to both droughts and floods is high. Previous studies have shown that the Ankang region is one of the most frequently flooded regions in the northwest (Department of Geography, Shaanxi Normal University, 1986; Ankang City Local History Compilation Committee,
510   2004), with a highly uneven distribution of precipitation over four seasons. After 1950, although the overall upper HRB was drought-prone and the frequency of floods tended to decrease, the frequency of large floods increased significantly, among which the flood events with peak flows exceeding 19,000 m³/s occurred in 1965, 1968, 1974, 1983, 1984, 1987 and 2005 in Ankang (Yin et al., 2010). In comparison, although droughts in the Ankang area are less frequent than floods, they often last longer
515   and have a huge impact on agriculture, making it the most vulnerable area for agricultural droughts in Shaanxi province (Zhang and Yin, 2012; Xu, 2016).

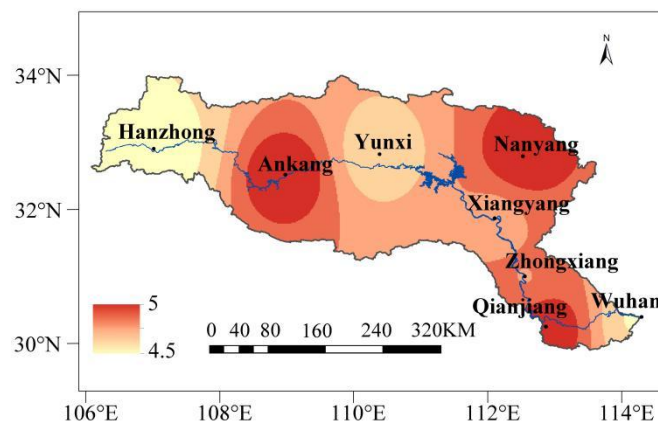
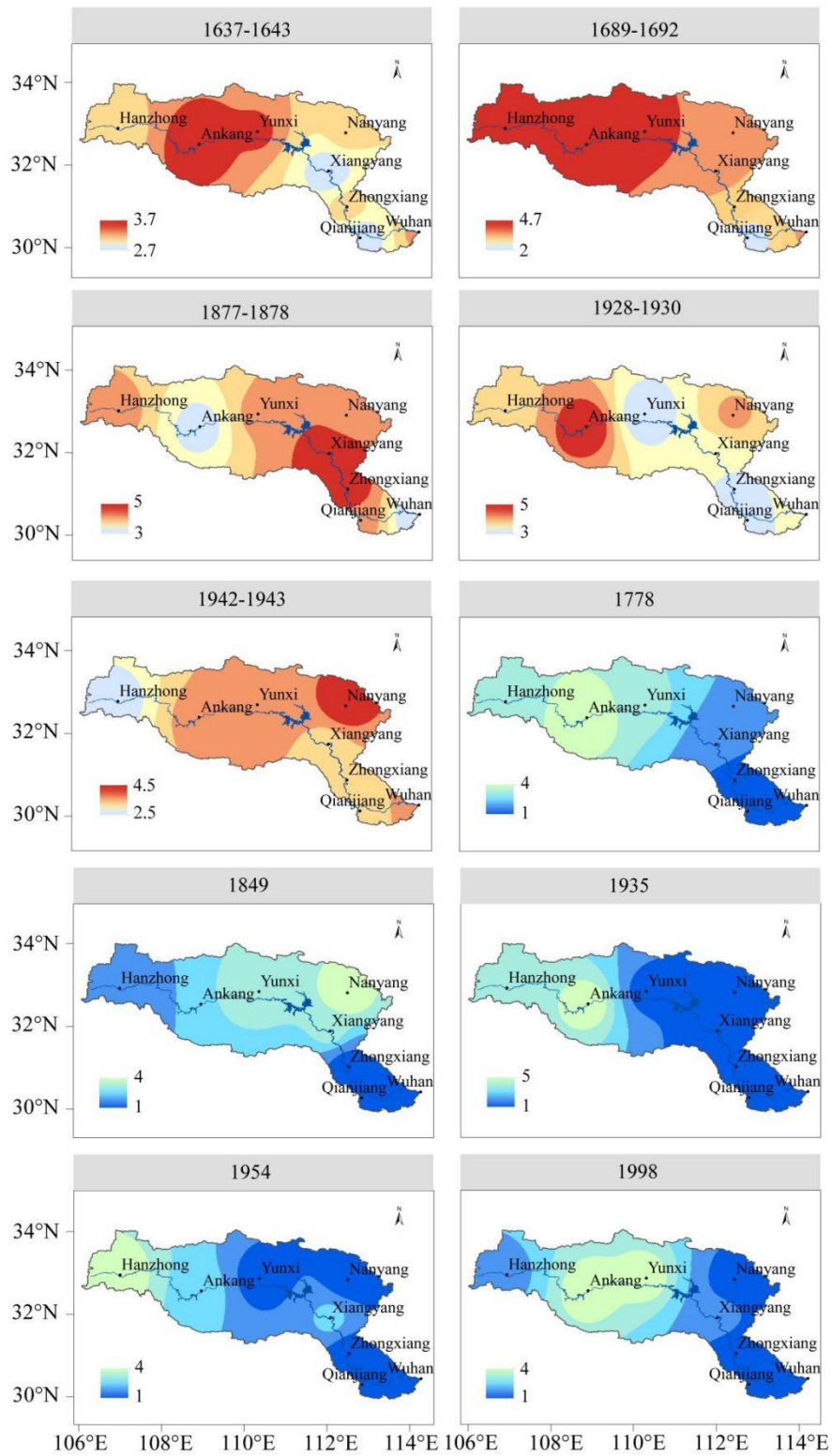



Figure 7: Distribution of average flood grades for each site corresponding to the severest flood years in each century. The color bar indicates the grade of drought and flood.

In order to examine the association of the droughts and floods of the HRB with the severe droughts and floods in other regions, we made a compound analysis of drought and flood grades in the HRB when severe droughts occurred in North China (inc. the lower reaches of the Yellow River and the North China Plain) and severe floods occurred in the Yangtze River. Figure 8 show the results for 5 representative severe droughts of North China (1637–1643, 1689–1692, 1877–1878, 1928–1930 and 1942–1943 were selected, respectively, based on Wang, 1999; Tan, 2003; and Qu et al., 2018), and 5 representative severe floods in the Yangtze River (1788, 1849, 1935, 1954 and 1998 were selected, respectively, based on Tao et al., 1998; Luo, 2006; Yang and Zheng, 2008; and Li and Zhou, 2020). It was found that the middle and lower HRB was more sensitive to floods in the Yangtze River basin, while the upper HRB was more correlated with droughts in North China. In order to verify the correlation between the HRB and North China, the drought and flood grades of the eight sites in the HRB were correlated with the average grade series of North China (Figure 9; Central Meteorological Bureau, 1981). Significant positive correlations can be seen for each of the eight sites in Figure 9. Among them, seven sites have significant correlations at the $p<0.01$ level, and one site (Wuhan) has a significant correlation at the $p<0.05$ level. The higher positive correlations of drought and flood grades with those of North China on a whole are in the upper reaches of the HRB, and the lower reaches of the river sees a lower correlation.

545 **Figure 8: The spatial distribution of average drought and flood grades in the HRB during severe droughts in North China (1637–1643, 1689–1692, 1877–1878, 1928–1930 and 1942–1943) and severe floods in the Yangtze River basin (1788, 1849, 1935, 1954 and 1998). The color bar indicates the grade of drought and flood.**

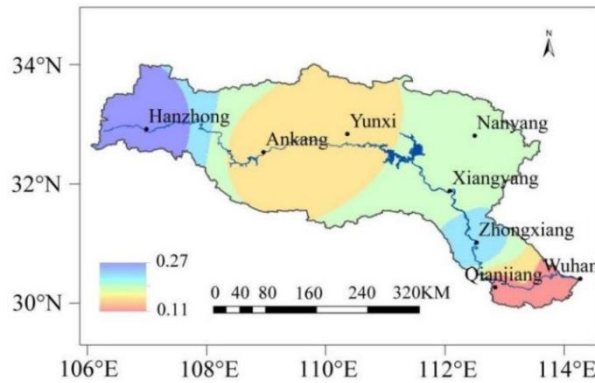



Figure 9: Spatial distribution of Pearson's correlation coefficients of drought and flood grades between eight sites of the HRB and North China on average (1470–2000). The correlation coefficients for Hanzhong, Ankang, Yuxi, Nanyang, Xiangyang, Zhongxiang, and Qianjiang are significant at the 0.01 level, and that for Wuhan is significant at the 0.05 level.

The South-North Water Diversion Middle-Route Project, which transfers water from the Danjiangkou Reservoir in the upper HRB to the North China Plain, is a huge hydro-project for supporting North China's sustainable development. Therefore, the synchronous encounter probability of rich-poor precipitation between the water source area in the upper HRB and the water-receiving area in the North China Plain is an important issue for inter-basin water resources deployment, which is directly related to the operability and benefit of the South-North Water Diversion Project (Chen et al., 2007; Gu et al., 2012). Since the mid-20th century, unfortunately, the probability of the co-drought in each basin of the South-to-North Water Diversion Middle-Route Project's water source and recipient areas has been at a historical high, and the water transfer from the Danjiangkou Reservoir to the North China Plain has been under great pressure (Ren et al., 2011; Qin et al., 2021).

Previous studies have also shown that the frequency of synchronous occurrence of droughts between the water source and the water-receiving area is the highest in the non-flood season. However, the precipitation in the water source area in the non-flood season is much smaller than the precipitation in the flood season, so the amount of the dry-season water that can be transferred north is minimal (Yan et al., 2007). On an annual scale, when the most desirable water-transfer scenarios were taken as a premise, the synchronous encounter probability of rich-poor precipitation in the North China Plain and the upper HRB was only 24% (Zheng and Liu, 2000). In addition, the probability of co-drought events in the upper HRB and the Haihe River Basin (The largest water system in North China) shows an increasing trend throughout the year under two future climate change scenarios of RCP4.5 and RCP8.5. In particular, the probability of experiencing co-drought in the flood season and co-severe drought in the non-flood season may increase significantly (Yu et al., 2018).

However, most of the previous studies were focused on analyses of instrumental precipitation data, and a comparative study of more than 100 years between the HRB and North China was much needed. This study shows that drought conditions in the upper HRB and North China also had a positive correlation on a long time period of nearly 600 years. Therefore, it is urgent and necessary to take measures for scientific regulation and reasonable configuration of the South-North Water Diversion Middle Line Project, so that the unfavorable impact of the synchronous encounter probability of rich-poor precipitation between the water source and the water-receiving area could be reduced as much as possible.

4 Discussion

4.1 Factors influencing the variability of extreme droughts and floods

590 It is generally accepted that the amount of precipitation over most of China is clearly influenced by the variability of the Asian monsoon (especially the Asian summer monsoon, i.e., East Asian summer monsoon and South Asian summer monsoon) and by ENSO (i.e., El Niño and La Niña) events (Zhu, 1934; Niu et al., 2004; Hao et al., 2008; Wang et al., 2020; Gao et al., 2017). In terms of monsoon influence, because the HRB is located at the junction of Central, North and Northwest China, it may be 595 affected by both East Asian and South Asian summer monsoon (Su, 1981; Yin, 2015).

  Figure 10 shows a comparison of extreme drought and flood events per 30 years in the HRB (the first time period is 1426–1429 and the last is 2000–2017) with the East Asian summer monsoon index and the South Asian summer monsoon index (i.e. Asian summer monsoon index). From the multi-decadal to century scale, the following correspondence can be found that:

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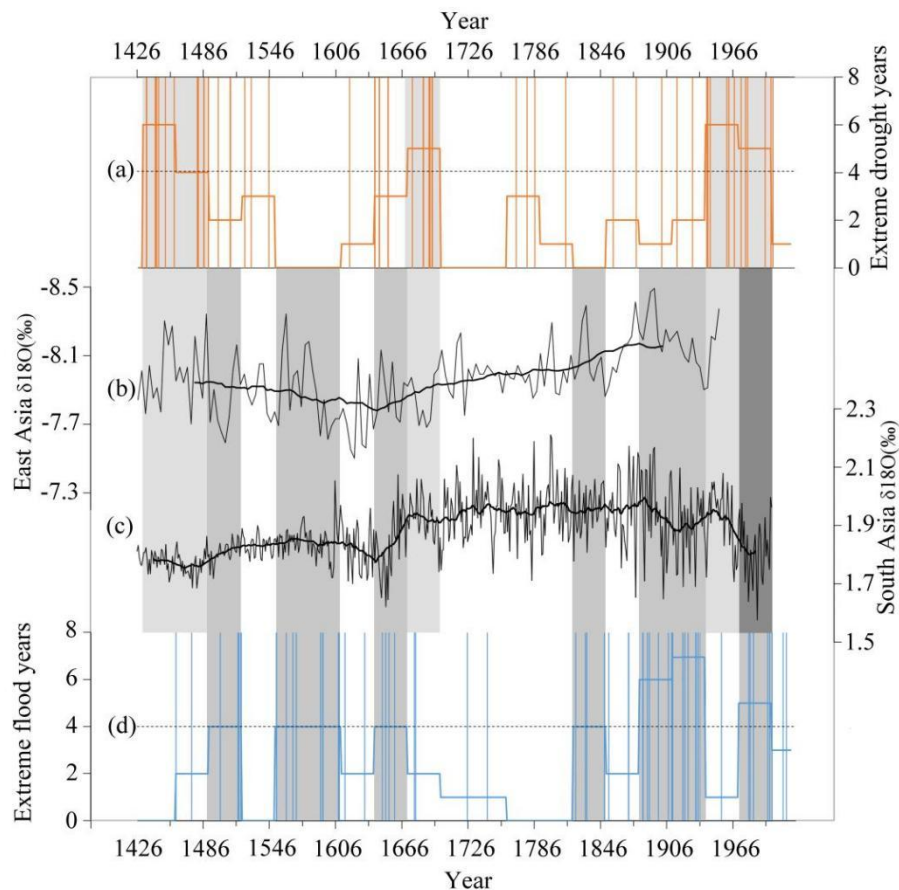
Figure 10: Comparison of the HRB extreme drought/flood years with the East Asian summer monsoon index and South Asian summer monsoon index as indicated by δ18O records (‰). The light grey areas represent periods of the high frequency of extreme drought, the medium grey areas represent periods of the high frequency of extreme flood, and the dark grey areas represent periods of high co-occurrence of extreme 605 drought and flood. (a) Extreme drought years. Vertical line shows the individual extreme drought years, and

the ladder is the number of extreme drought years per 30 years. (b) East Asian summer monsoon index, 1426–1949 (Zhang et al., 2008b). The thick black line indicates the 30-year sliding average. (c) South Asian summer monsoon index, 1426–2000 (Shi et al., 2017). The thick black line indicates the 30-year sliding average. (d) Extreme flood years. The vertical line shows the individual extreme flood years, and the ladder is the number of extreme flood years per 30 years.

(1) In the 15–17th century, when the Asian summer monsoon was generally weak, there were 24 extreme drought events and 22 extreme flood events in the HRB, and extreme drought events were relatively more likely to occur. The weak Asian monsoon seems to be in favor of extreme drought occurrence on the multi- to century scales.

(2) In the 18–19th century, when the Asian summer monsoon gradually strengthened, there were six extreme drought events and 12 extreme flood events in the HRB, which were generally lower than those in previous period in occurrence of extreme drought and flood events. Specifically, there were relatively few extreme events in the 18th century and an increase in extreme events in the 19th century, with 10 extreme floods and three extreme droughts in the 19th century, more than three times as many extreme floods as extreme droughts. This sharp contrast between extreme droughts and extreme floods may illustrate that the increased Asian summer monsoon on multi- to century scales was conductive to more rainstorms and floods in the HRB. However, the correspondence of the stronger summer monsoon and the low occurrence of both extreme droughts and floods in the 18th century may indicate the complexity of the mechanisms by which the extreme drought and flood events in the basin occur.

(3) The second half of the 19th century and the 20th century saw a significant strengthening until the early 20th century, and then a slight weakening afterward, of the Asian summer monsoon, and a marked increase in extreme drought and flood events, with 16 extreme drought events and 21 extreme flood events occurring in the study region. Interestingly, in the strengthening stage of the monsoon, the extreme floods increased more obviously, and in the weakening stage of the monsoon, the extreme droughts came more, indicating once more that strengthened monsoon was generally in favor of more rainstorms and floods, and weakened monsoon was possible to cause more extreme droughts. Other studies (Huang et al., 1999; Lu, 2002; Niu et al., 2004) showed that, in the second half of the 20th century, abrupt changes in Asian atmospheric circulation and a weakening of the summer monsoon led to an increase in drought events in northern China. Ye and Zhao (1995) found that extreme droughts and floods in the 20th century have broadly evolved through a process of major floods followed by a shift to more droughts, which is also consistent with the results of this analysis.

The correlation between the average of extreme drought/flood grades in the HRB and the average of Asian summer monsoon indices (i.e. the average of East Asian summer monsoon index and South Asian summer monsoon index) at a 30-year time window was analyzed. There was a significant negative correlation between them ($p<0.01$). This once again suggests that the multi-decadal variations in the frequency of extreme drought/flood events of the HRB are influenced to some extent by changes in the strength of the Asian summer monsoon, with relatively more extreme drought events when the monsoon is weak and more extreme flood events when the monsoon is strong.

The correlation coefficients between the frequencies of strong ENSO events (per 30 years) and extreme droughts/floods (per 30 years) in the HRB was also calculated for the period of 1530–1979. We found that extreme floods are significantly positively correlated with strong El Niño events at a multi-decadal scale, and the correlation passed the significance test ($p<0.05$) (Figure 11). Extreme droughts and strong El Niño/La Niña events and extreme floods and strong La Niña events also showed

positive correlations, but they did not pass the significance test ($p<0.05$). This suggests that, on a multi-decadal scale, the strong ENSO events probably have some influence on annual and summer precipitation in the HRB, and the strong El Niño events have a greater impact on extreme floods than extreme droughts in the river basin on a whole.
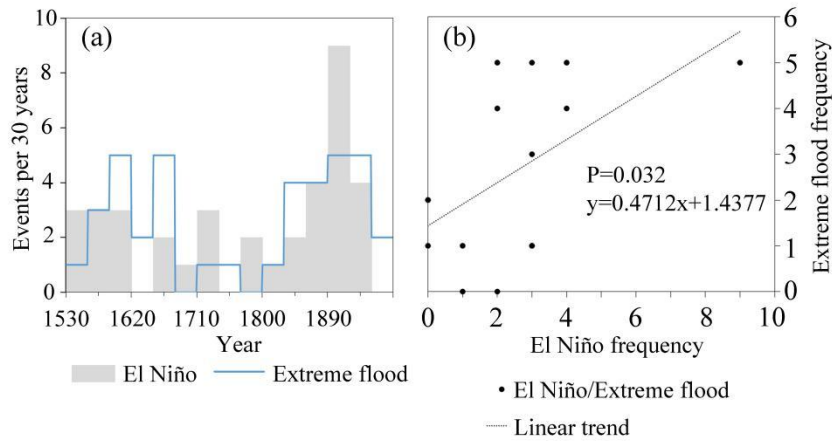
Figure 11: Correlation of extreme floods in the HRB and strong El Niño frequency (per 30 years) during 1530–1979. a. Frequency distribution of extreme floods in the HRB and strong El Niño events; b. Correlation between frequencies of extreme floods and strong El Niño events.

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Yin (2015) found that the upper Hanjiang River was more prone to flood disasters in years with stronger El Niño at the end of the previous year or at the beginning of the same year, and in years when El Niño was switched to La Niña. They also found that, during the weak Asian summer 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 reach. Conversely, during the strong Asian summer monsoon, the upper HRB is prone to heavy rainfall, even floods, in summer, and continuous rain or floods in autumn (Yin, 2015).

Therefore, as a transitional zone between northern and southern China and between the subtropical and warm temperate zones, to a certain extent, the HRB is influenced by the variability of Asian monsoon strength. In addition, as one of the strong signals of inter-annual variability in sea-air interactions, the ENSO events strongly influence the strength of the Asian summer monsoon (Wang et al., 2020), leading to an abnormal pattern of the HRB summer rainfall. However, precipitation and extreme droughts/floods are also affected by other environmental factors and the complex interactions among the different factors, such as volcanic eruptions, AMO and PDO. The association of the Asian monsoon/ENSO and the HRB extreme drought/flood events in history is not straightforward. This may be the reason why the correspondence between precipitation and monsoon is still controversial in proxy data and modeling studies (e.g., Lu et al., 2019; Shi et al., 2021). It is also worth indicating that, due to the space limitation, this study provides only a very preliminary discussion of the relationship between extreme droughts/floods of the HRB with Asian summer monsoon and ENSO. There may also be a difference in the monsoon's impact on precipitation between the upper and lower reaches of the Hanjiang River. Therefore, the relationship of historical basin-wide extreme droughts/floods in the HRB with the Asian Monsoon Index and ENSO events on decadal to multi-decadal scales obviously needs to be further investigated in the future.

4.2 Limitations of the methods used

Although a great effort has been made to collect historical documents and reconstruct the extreme droughts and floods of almost last six centuries in the HRB, the methods used in this study to reconstruct the historical drought and flood grade series has the following two limitations:

First of all, the reconstruction method of the Atlas is to take the year as unit, combine the drought and flood disasters in spring, summer, and autumn within that year, and base the grading on the most severe disasters recorded. When both droughts and floods occur in a given year, the disaster situation in summer tends to be selected for our statistics. This definition is consistent with the climate in most of China, especially suitable for areas where rice is mainly grown (The HRB is dominated by rice cultivation) (Chen, 2020). However, droughts and floods are also frequent in the HRB in other seasons (Ding and Zheng, 2020), which result in the neglect of climate abnormality in other seasons. Meanwhile, not all drought and flood disasters in historical documents clearly indicate the time of occurrence (season, month, etc.), so it is possible that certain extreme events in spring and autumn were wrongly assigned as disasters occurring in summer (Chen, 2020).

Secondly, the method of dividing time points according to the number of historical period materials also suffers from the unavoidable uncertainty of using proxy data for reconstruction work. In this study, the uncertainties are mainly in the subjective description of historical information, which is unavoidable in grading. Because historical materials include a variety of information, there are complex relationships between different carriers and different records, which may lead to subjectivity and ambiguity. This cannot be avoided entirely even if we do not base the grading on the linguistic descriptions of historical materials alone when selecting the available historical materials (Yang and Han, 2014).

5 Conclusions

This study investigated the multi-decade to centennial scale variation of extreme drought and flood over the HRB 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 52 extreme flood events occurred from 1426–2017, equivalent to an extreme drought event per 13 years and an extreme flood event per 11 years. Extreme flood events occurred slightly more frequently than extreme drought events.

(2) The relatively more frequent 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.

(3) More frequent extreme flood events occurred in the 16th to 17th centuries and the 19th to 20th centuries. The highest frequency of extreme flood events was in the 19th and 20th centuries, while the 18th century underwent the lowest frequency of extreme flood events.

(4) The frequency of both extreme drought and flood events was low in the 18th century, when there was probably a more favorable climate in the HRB compared to other periods. However, the 20th century saw a high frequency and increased risk of both extreme drought and flood events in the HRB.

(5) The historical high-frequency extreme droughts centered in the middle reaches of the HRB, and the high-frequency extreme floods centered in the lower reaches. The frequency of the extreme

droughts and floods was higher in the middle and lower reaches than those in the upper reaches.

(6) The occurrence of extreme droughts and floods in the upper HRB are more strongly positively correlated with those in North China.

Data availability. All reconstructed data for the identification of extreme drought and flood events used in this study are available in the Supplement. Dataset of East Asian summer monsoon are available at www.ncdc.noaa.gov/paleo/study/8629 (NOAA, 2008) and South Asian summer monsoon are available at www.ncdc.noaa.gov/paleo/study/17369 (NOAA, 2014). Chronology of El Niño and La Niña events are available at 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.

Author contributions. GR and BH designed the research and guided the writing; YY and ZH guided the development of the methods; XZ conducted the analysis and PZ guided the technical part; XZ reconstructed the drought and flood grade series, analysed the data, drew the figures and drafted 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 (2018YFA0605603). Thanks are due to Prof. X. Q. Fang for his instructive advice. The authors also thank to G. W. Yang, Y. Qin and J. J. He for their technical assistance in drafting the paper.

Financial support. This research is supported by the National Key R&D Program of China (Grant no. 2018YFA0605603).

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