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Severe Historical Droughts Carved on Rock in the Yangtze

Jun Qin, Ailin Shi, Guoyu Ren, Zhenghong Chen,
Yuda Yang, Xukai Zou, and Panfeng Zhang

ABSTRACT: The White Crane Ridge (WCR) Rock Fish, now submerged under the backwater of the Three Gorges Reservoir in the Yangtze River, are affirmed as one of the earliest hydrologic observations ever made in any large river in the world. The usually in-water monument provides highly valuable historical records of severe droughts in the upper Yangtze over the last 1,200 years. This article updated the historical drought chronology previously developed based on the WCR inscriptions, which can be applied in assessment of extreme climatic and hydrological risks, and also made a preliminary analysis of changes of the severe drought frequency during the last thousand years in the upper Yangtze. The analysis shows that the severe droughts occurred more frequently during the Medieval Climate Anomaly (MCA), relatively less so during the Little Ice Age (LIA), and once again more often under the background of modern global warming. It was suggested that a generally warmer Euro-Asian continent during the MCA was in favor of the stronger East Asian summer monsoon, and the resulting less precipitation and more severe droughts of the Yangtze and the lower water level at the Three Gorges area on the centennial scale, and vice versa for the period of the LIA. The results would help in understanding the causes and mechanisms of the regional climate change and variability, and also in taking measures in the fields of the watershed management to cope with the long-term change in climatic and hydrologic droughts.

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Corresponding author: Guoyu Ren, guoyoo@cma.gov.cn

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AFFILIATIONS: Qin, Shi, Zhang—Department of Atmospheric Science, School of Environmental Studies, China University of Geosciences, Wuhan, China; **Ren**—Department of Atmospheric Science, School of Environmental Studies, China University of Geosciences, Wuhan, and Laboratory for Climate Studies, National Climate Center, China Meteorological Administration, Beijing, China; **Chen**—Hubei Meteorological Service Center, Wuhan, China; **Yang**—Center for Chinese Historical Geographical Studies, Fudan University, Shanghai, China; **Zou**—Laboratory for Climate Studies, National Climate Center, China Meteorological Administration, Beijing, China

The long-term variation in precipitation and drought frequency in the past centuries is key to understanding the background and causes of the recent change in extreme climate events in a large river basin, and it is also important for the studies of the impacts of climate change on regional natural and social systems (Brázdil et al. 2006; Cook et al. 2010). However, a great challenge has been posed to investigators because the scarcity of high-resolution proxy records in some of the humid large river basins of the world. This is especially true for the upper reach of the Yangtze River, where much precipitation occurs in the Sichuan basin and its surrounding areas, and the tree-ring data are usually less available for reconstructing the historical precipitation and droughts (Liu et al. 1996; Wu et al. 2008).

Near the Three Gorges area of the Yangtze, an enormous rock lies within the waters of the river; it is known as White Crane Ridge (WCR) or Baiheliang. The 1,600-m-long and 15-m-wide ridge, which is composed of sandstone on its surface, is located close to the boundary between the upper and middle reaches of the Yangtze. Generally, the rock was nearly submerged beneath the water surface throughout the year; it was exposed to air only during the middle to late winter and early spring seasons of drier years.

WCR has been well known in China since ancient times because its emergence from beneath the water surface had special significance: early drought in the upper Yangtze was most likely followed by favorable climatic conditions and a bumper harvest in the following growing season. Ancient people who lived since at least 1,200 years ago used to inscribe characters and images of fish on the surface of the ridge when it emerged above the water. This image of fish is now known as Rock Fish (RF). The ancient people also used to hold a ceremony to mark this occasion during which they measured and recorded the depth of the water level from a pair of reference RF, with the eyeball center of the left one (used for only reference level later) resting at an elevation of 138.04 m above mean sea level (MSL) (Sun and Chen 2014; Sun 2016).

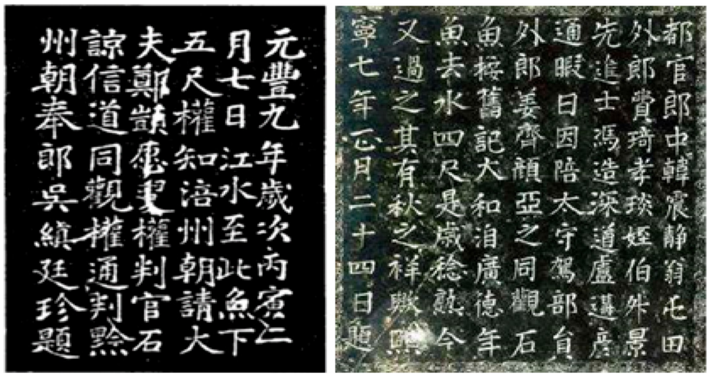
The ancient local chronicles of Fuling County provide the following description: “Pairs of fish were carved on the ridge, all with 36 scales; one held a branch of glossy ganoderma while the other held a lotus flower in their mouths; a Dou (an ancient container for measuring grain) and a weigh beam laid beside them” (Fig. 1). In AD 1254, a local officer and poet Shuzi Liu noted the following: “The Rock Fish on the ridge were carved by people of the Tang Dynasty (AD 618–907). The inscriptions read that RF images appear every three to five years or every about ten years, and when they come out of the water, the following year will experience a bumper harvest.” (Institute of Ancient Documents 1998).

Figure 2 shows two rubbings of the inscriptions on WCR, which documented the change magnitudes of the river water relative to the reference fish in AD 1074 and AD 1086. The original dates were recorded as Chinese lunar calendar, and they have been translated to the Gregorian calendar. The rubbing of AD 1074 said in ancient Chinese that a local officer came to observe the RFs accompanying a prefecture chief on 24 January 1074 (Chinese lunar calendar), and they saw the river water went 4 chi below the reference fish on the day. They thought that this was the sign of auspiciousness in autumn.

Fig. 1. (left) The surface appearance of WCR before the submergence beneath the water by the Three Gorges Dam and (right) the rubbing of the carved double fish images and inscriptions on WCR. The double Rock Fish were recarved in the Qing Dynasty, which is a little bit different from those originally carved in the Tang Dynasty.

Most of the inscriptions and carved fish images are scattered throughout the central section of WCR. More than 170 areas of inscriptions with more than 10,000 words have been found. The earliest inscriptions that are presently readable were carved in AD 764, and the latest ones date to AD 1963. There are far fewer Rock Fish images on the upper part of the ridge; only 18 are identifiable. The inscriptions and images document extremely low water levels in more than 72 years, and some clearly record the depths of the water level from the reference RF in chi (Chinese unit of length). Thus, they systematically record extreme hydroclimatic droughts in more than 1,200 years in the upper Yangtze.

Several researchers made investigations of RF emergence years and extremely low water level at WCR. In particular, Sun (2016) has recently conducted the most comprehensive and complete textual research so far, and reported a historical chronology of RF emergence years and low water level in the upper reaches of the Yangtze River. Before this excellent work, other researchers also made a lot of investigations (e.g., Yangtze Valley Planning Office and Chongqing City Museum 1974; Wang 1998; Qiao and Chen 1999; Yi 2003). However, all of the previous works were concentrated on construction of the historical chronology of RF emergence years and the identification of the historical severe droughts in the upper basin of the WCR. There is a need to update the chronology of RF emergence years to present (2003), and also to further examine the long-term change in frequency of severe droughts in the upper Yangtze River.



元豐九年歲次丙寅正月七日江水至此魚下五尺權知涪州朝請大夫鄭顗巖叟權判官石諒信道同觀權通判黔州朝奉郎吳縝廷珍題

都官郎中韓震靜翁屯田外郎費琦孝琰姪伯外景先進士馮造深道盧遘彥通暇日因陪太守駕部貟外郎姜齊顏亞之同觀石魚按舊記大和泊廣德年魚去水四尺是歲稔熟今又過之其有秋之祥歟熙寧七年正月二十四日題

Fig. 2. Rubbings of the inscriptions on WCR: (left) "River water reaches 5 chi below the fish on 7 February 1086 (Chinese lunar calendar)" and (right) "River water goes 4 chi below the fish on 24 January 1074 (Chinese lunar calendar), and this is the sign of auspiciousness."

In this paper, we report an updated drought chronology of the upper Yangtze River, which is mainly based on the chronology of RF emergence years by Sun (2016) and Qiao and Chen (1999) for the historical time, and an examination of the relationship between RF emergence events and the modern records of water level of a nearby hydrologic station for the period after AD 1963. A preliminary analysis of the severe drought frequency change during the last thousand years plus based on the drought chronology is also shown in this paper.

Location and physiographical features

WCR is located in Fuling District, Chongqing City (29°43′N, 107°24′E). It is now under the upper river water of the Three Gorges, which is near the division of the upper and middle reaches of the Yangtze (Fig. 3).

The Yangtze flows eastward in this area of the Sichuan Basin, forming the famous Three Gorges (Qutang, Wu, and Xiling Gorges) when it crosses the north–south-oriented Wushan Mountains. The Three Gorges Dam was built in the section of the river. The reservoir was in operation in 2003, and WCR and all of the inscriptions and RF images carved on it had been impounded by the backwater since then. The Baiheliang Underwater Museum was constructed to preserve valuable cultural relics and historical sites.

Climate in this area is characterized by a hot and humid summer and a cool and dry winter, with a January mean temperature of 7.1°C and July mean temperature of 29.3°C, and an annual total precipitation of around 1,200 mm. The highest water level of the Yangtze at this section is reached in July–August, and December–March register the lowest water level. The runoff is mainly supplied by rainfall in the upper reach of the river, and the melting water of snow and glacial in the Qinghai–Tibetan Plateau supplies only about 13% water to the runoff.

Establishment of drought chronology

Some of the inscriptions and RF images on WCR were copied, kept as rubbings, and published in historical documents in different time periods, but still some of them were kept intact at the scene. Since the 1970s, several groups had attempted to collect and compile the inscriptions and RF images based on various documents and field investigations. In 1974, the Yangtze Valley Planning Office and the Chongqing City Museum (YVPO/CCM) jointly launched a project to collect various documents all over the country and the in situ inscriptions and RF images, and finally published a comprehensive report on historical droughts recorded on WCR; the report included a chronology of the extremely severe droughts of 27 years in which the RFs emerged from AD 764 to AD 1796, and the simultaneous water levels below the reference RF for some of the years (Yangtze Valley Planning Office and Chongqing City Museum 1974). The chronology was later supplemented and corrected, to a larger extent, by a few studies (Wang 1998; Qiao and Chen 1999; Yi 2003; Sun 2016).

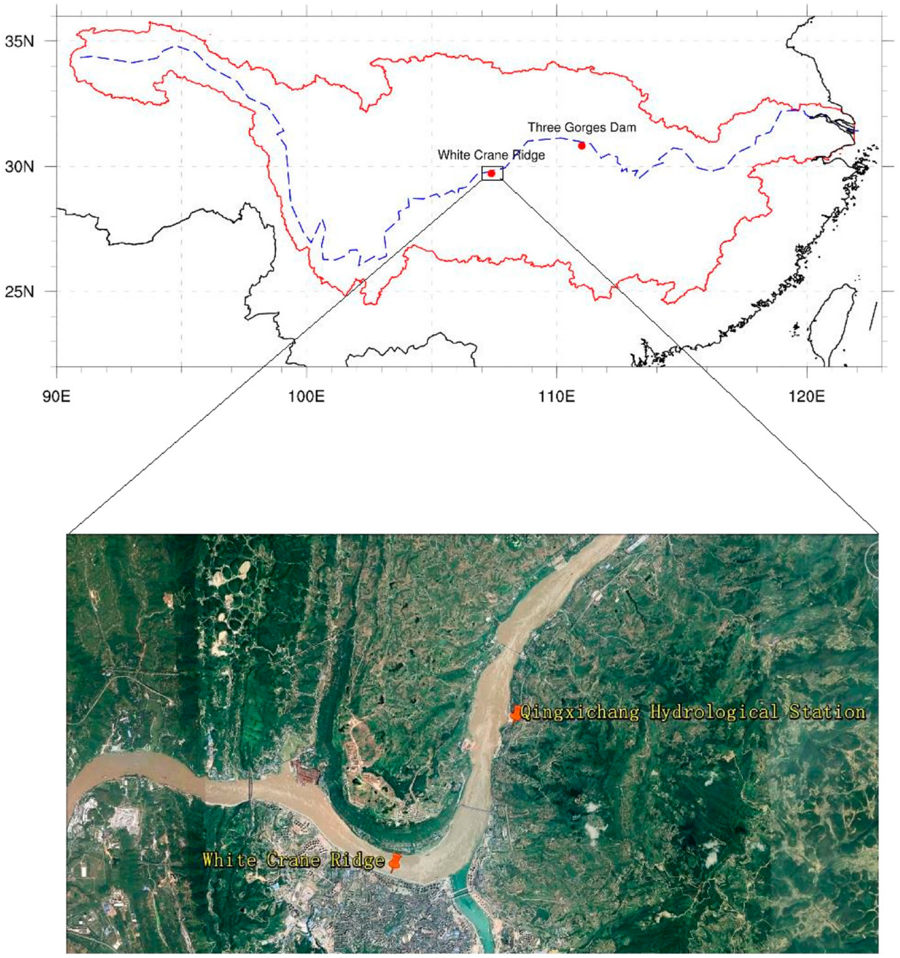


Fig. 3. The location of WCR (Baiheliang), QHS, and the Three Gorges Dam in the Yangtze River. (top) The Yangtze River basin, with dashed blue lines indicating the main stream, and solid red lines the boundary of the basin and (bottom) locations of WCR and QHS.

Wang (1996, 1998) showed the information of the ancient water levels for 15 of the 27 years as reported by the YVPO/CCM, based on the comparison of the inscriptions and modern river-water-level records, and compared the historical extremely low water levels to those modern years. Qiao and Chen (1999) supplemented the 22 additional RF emergence years recovered in the work by YVPO/CCM, which were not included in Yangtze Valley Planning Office and Chongqing City Museum (1974), with the support by the colleagues from the YVPO. Yi (2003) reported the extremely low water levels of five years (1952, 1963, 1973, 1979, and 1987) in modern time based on the hydrologic records.

Recently, Sun (2016) made the most painstaking investigation of the RF emergence years on WCR and low water level of the upper Yangtze River so far. He checked and adjusted the ancient water level values as reported by YVPO/CCM and Wang (1996), and reported an updated chronology of RF emergence years and dates, including the information of the simultaneous water levels below the reference RF. There are 95 items and 66 years of records total in the chronology, with a few years having more than one item of record. The work of Sun (2016) laid a solid data foundation for studies of historical severe droughts in the upper Yangtze River.

On the basis of previous works, in particular those of Sun (2016) and Qiao and Chen (1999), we updated the chronology by including the estimated RF emergence years after 1963, the last year for the local governments to observe and hold a ceremony in case of the RF emergence and extremely low water level. In addition, the items of record in a year in Sun (2016) were combined into one, with the lowest water level of the records (if any) registered as the year's water level below the reference RF.

The estimations of RF emergence years after 1963 were performed based on instrumental records of the river water level at the downstream Qingxichang Hydrologic Station (QHS), which is situated 12.1 km away from WCR.

Over the period containing instrumental records (1941–2003), the emergence of the RFs from beneath the water has been conclusively documented in previous publications for exactly three years, namely, 1941, 1963, and 1973 (Wang 1998; Qiao and Chen 1999; Sun 2016). By comparing the different indicators of the water level during the dry-season, we found that an annual consecutive 7-day minimum water level of 136.34 m at QHS constitutes a good threshold for judging the emergence of the RFs at WCR. The applicability and validity of this threshold are confirmed by using the dry-season (January–March) mean water level of 136.82 m at QHS.

The most recent document regarding RF emergence is dated to 1963. To extrapolate past records to the impoundment time of the Three Gorge Reservoir in 2003, we use nearby hydrologic station records to estimate the years of RF emergence. The instrumental records of the Yangtze water level at the downstream QHS situated 12.1 km away from WCR are used in the estimation.

The elevation of the reference RF is 138.04 m MSL (Sun 2016). During 1941–2003, the RF emergences in 1941, 1963, and 1973 have been confirmed (Wang 1996; Sun 2016). By comparing the different indicators of the water level during the dry season, including the annual consecutive 7-day minimum water level, the dry-season (December–March) mean water level and the lowest 1-month mean water level, we find that the annual consecutive 7-day minimum water level of 136.34 m at QHS is the highest among the three years, and it can therefore be used as the threshold for the emergence of the RFs at WCR (Table 1). The applicability of this threshold is further confirmed by using the dry-season mean water level of 136.82 m at QHS that also registered the highest value among the three documented years in 1941.

Although RF emergence was reported in the local news in both 1966 and 1983 (Zhang 1992; Editorial Board 1993), it was not mentioned in any publications from authority organizations or research groups, indicating that the appearance of the RFs during the dry season was far from sufficient. The annual consecutive 7-day minimum water levels of these two years rank ninth and tenth, respectively, and they are only slightly higher than the 1941 water level (Fig. 4). This fact supports the selection of an annual consecutive 7-day minimum water level of 136.34 m as a threshold for present-day RF emergence.

Table 1. Comparison among the average annual consecutive 7-day minimum water level, the lowest 1-month mean water level, and average dry-season water level at Qingxichang Hydrologic Station for the 8 years of RF emergences during 1941–2003 (unit: m MSL). Boldface indicates the documented years of RF emergence at White Crane Ridge.

No.	Year	Average annual consecutive 7-day minimum water level	Year	Lowest 1-month mean water level	Year	Average dry season water level
1	1979	136.13	1978	136.29	1979	136.55
2	1978	136.18	1979	136.39	1960	136.60
3	1960	136.26	**1941**	136.43	**1963**	136.63
4	1974	136.27	1960	136.47	1978	136.66
5	**1963**	136.29	**1963**	136.48	1974	136.72
6	1987	136.30	**1973**	136.50	**1973**	136.72
7	**1973**	136.34	1987	136.50	1987	136.77
8	**1941**	136.34	1966	136.55	**1941**	136.82

In addition, the RFs reportedly emerged during the winter of 1952/53 (Qiao and Chen 1999); both the annual consecutive 7-day minimum water level (136.98 m) and the dry-season mean water level (137.55 m) were much higher than the above thresholds, and the lowest 1-month mean water level (137.18 m) in this year was also higher than those of the years in which the RFs did not emerge. We thus believe that the abovementioned emergence of the RFs in 1952/53 was incorrect or that they emerged only for a very short period in any month of the dry season. The year of 1953 is therefore not considered in determining the water level threshold for RF emergence, and thus, it was discarded from the updated chronology.

According to the abovementioned threshold and the observational data from QHS, the years in which the RFs emerged before 2003 (the year of impoundment of the Three Gorge Reservoir) are determined as 1979, 1978, 1960, 1974, and 1987 in addition to the already-known years of 1941, 1963, and 1973. Considering these three documented events, the RFs emerged a total of eight years during 1941–2003 (Fig. 4).

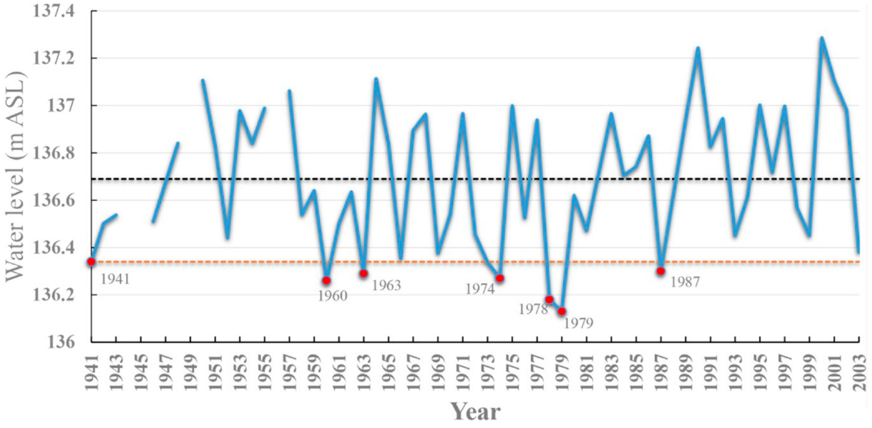


Fig. 4. Annual consecutive 7-day minimum water levels at QHS during 1941–2003. Yellow dotted line is the threshold water level (136.34 m), and black dotted line is the average annual consecutive 7-day minimum water level during 1941–2003 (136.69 m). Red point denotes the year when annual consecutive 7-day minimum water level is below the threshold water level. Hydrologic records are missing for four years: 1944, 1945, 1949, and 1956.

We also find that if the dry-season mean water level of 136.82 m at QHS is taken as a threshold of RF emergence, the estimated eight years are exactly the same as those determined by the annual consecutive 7-day minimum water level of 136.34 m despite the ranking difference of the years, indicating that the two thresholds are both applicable and interchangeable.

Consequently, we estimated that the RFs emerged in additional five years before 2003: 1979, 1978, 1960, 1974, and 1987. Considering the three documented events in 1941, 1963, and 1973, the RFs emerged a total of eight years during 1941–2003, during which time the average annual consecutive 7-day minimum water level was 136.69 m MSL. For the eight years in which the RFs emerged, the average annual consecutive 7-day minimum water level was 136.26 m. We added these estimated years to update the chronology (Table 2).

WCR is located approximately 12.1 km upstream of QHS. Their water level difference is thus an essential parameter for calculating the ancient dry-season water levels of WCR.

According to the records of the Fuling County Culture Gallery, the difference between the RF and the water level was 1.45 m on 15 February 1963, which can be converted to a vertical height of 38 cm or a water level of 137.66 m MSL (WCR altitude is 138.04 m). The water level at QHS on the same day was 136.38 m MSL, and thus, the dry-season water level difference between the two sites was approximately 1.28 m.

The ancient inscriptions at WCR were made on an inclined plane, and thus, the distance between the elevation of the RF and the water level is not the vertical depth of the water level from the reference RF. Therefore, the original records of this distance had to be converted into vertical depths.

According to Sun (2016), the declination of the plane is 14.5°, and the slope is 0.26. The vertical depths of the water level from the reference RF will be the products of 0.26 and the original records. For example, the recorded distance between the RF and the water level was 1.45 m on 15 February 1963, and thus the vertical depth of the water level would be 0.38 m (37.7 cm).

Table 2. A chronology of RF emersion at White Crane Ridge in the Three Gorges area in the upper Yangtze River. (Note: The dry season ranges from January to March. The Three Gorges Dam began to store water in June 2003, so data for the 2003 dry season are not available).

Century	Year (water level below the reference RF in cm)
AD 700	764 (32)
AD 900	971, 989
AD 1000	1049, 1057, 1066, 1068, 1074 (33), 1086 (41), 1090, 1091, 1093
AD 1100	1100, 1102, 1107 (58), 1112, 1123, 1129 (49), 1132, 1133, 1135, 1136, 1138 (41), 1140, 1144 (8), 1145 (41), 1148, 1153, 1155, 1156 (8), 1157, 1167, 1171 (33), 1178 (25), 1179 (33), 1184, 1198
AD 1200	1202, 1208, 1220, 1226 (49), 1230, 1243, 1245, 1248, 1250, 1254, 1255, 1258
AD 1300	1312, 1329 (16), 1330 (41), 1333, 1384
AD 1400	1404, 1405 (41), 1453, 1459, 1471
AD 1500	1506, 1510, 1589 (8)
AD 1600	1672, 1684, 1685, 1695
AD 1700	1706, 1751, 1775, 1796 (65)
AD 1800	1813, 1875, 1881
AD 1900	1909, 1915, 1937, 1941(12), 1960 (20), 1963 (38), 1973 (12), 1974 (19), 1978 (28), 1979 (33), 1987 (16)
AD 2000	—

Different dynasties of China applied different length scales. During the last 1,200 years, the dynasties used the chi as unit of length. The conversions between chi and the modern metric unit of length were made referring to Metric System Evolution of Ancient China (www.360doc.com/content/16/0412/14/20418_550001726.shtml).

Verification of drought occurrence

To confirm the association between the hydrologic droughts and climatic droughts over modern time, we compare the recent years of RF emergence with the dry-season (January–March) mean climatic drought index series of the upper reach of the Yangtze River (above the Three Gorges Dam). The comparison is approximate only because of the rough temporal and spatial resolution.

The daily meteorological data are from the National Meteorological Information Center, China Meteorological Administration (CMA). There are 223 observational stations in the upper Yangtze region. The climatic drought index, comprehensive index (CI) of meteorological drought, was developed by the National Climate Center, CMA (Zhang et al. 2011). Basically, it takes accumulated daily precipitation of the last 30 and 90 days into consideration, and also applies the Penman–Monteith formula to calculate evaporation for obtaining a wetness term for the last 30 days. Larger negative values of the index indicate more severe meteorological drought. For example, $-2.4 < \mathrm{CI} \leq -1.8$ indicates a severe drought, and $\mathrm{CI} \leq -2.4$ indicates an extremely severe drought, according to the CI-based classification of the meteorological drought in China. The index has long been applied in the operational monitoring of meteorological drought in the CMA.

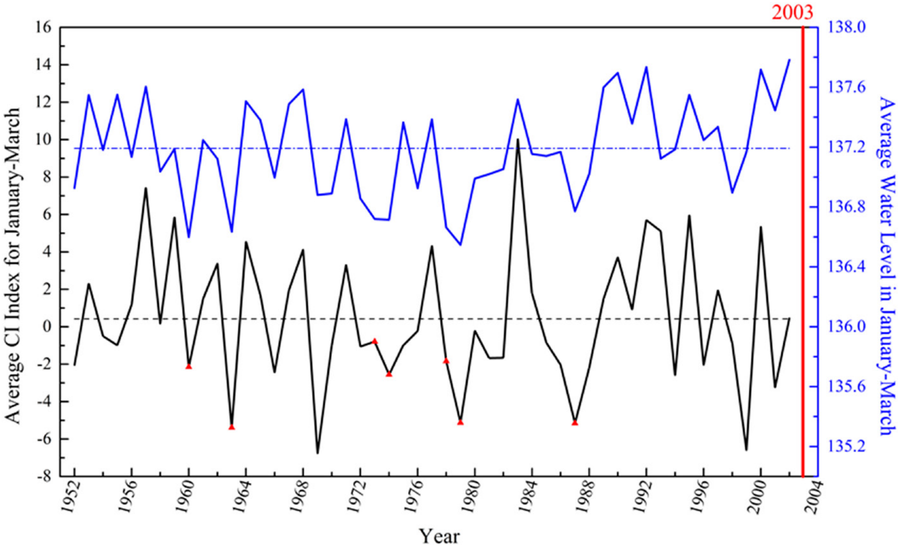


Fig. 5. Regional averaged dry-season (January–March) mean CI anomalies in the upper reach of the Yangtze River (black line) and average January–March water level at QHS (blue line) over the period 1951–2002. Red line shows the beginning impoundment year of the Three Gorges Reservoir, and the red triangle indicates the years of RF emergences.

We calculate the regional averaged dry-season mean CI of the upper Yangtze for the period 1951–2002, with regional climatic drought defined as annual mean CI ≤ −1.8 (Zou et al. 2010). Latitude–longitude grids of 1° × 1° are used to calculate the annual area-weighted values of CI referring to the method by Jones and Hulme (1996). Figure 5 shows the change in the regional averaged dry-season mean CI anomalies in the upper reach of the Yangtze over the period 1951–2002, as compared to the water level at QHS. The correlation coefficient of the CI anomalies and the water level is 0.66, which is significant at the 99% confidence level, indicating a significant influence of meteorological droughts on the water level near WCR. Moreover, the recent RF emergences as indicated in Fig. 4 all occurred in years of meteorological droughts (CI ≤ –1.8) except for 1973 when the severe drought may have occurred near WCR rather than in the whole upper basin of the river.

Table 3 shows the regional average monthly mean CI of the upper reach of the Yangtze River over the period 1951–2003. In the years of RF emergence at WCR, the CIs are almost all in negative values, and most of them are in large absolute values, indicating the severe droughts occurred in the preceding months in the region. The most severe climatic drought, with the dry-season mean CI reaching −5.39, was observed in 1963, when the water level at WCR fell 38cm below the reference Rock Fish. The slightest climatic drought since 1956 is also in correspondence to the smallest drop of water level (12 cm) in 1973 when the dry-season mean CI is only −0.79.

Table 3. Regional average monthly mean CI values of the upper Yangtze River over the period 1951–2003.

Year	January	February	March	Dry season
1960	−3.05	−2.94	−0.09	−2.15
1963	−4.70	−5.88	−5.49	−5.39
1973	1.18	−0.76	−2.76	−0.79
1974	−1.85	−2.07	−3.69	−2.56
1978	2.89	−4.11	−4.50	−1.84
1979	−5.50	−4.89	−4.96	−5.13
1987	−2.93	−6.00	−6.61	−5.16

Therefore, there is a good correspondence between the water level change and the upper Yangtze average CI values, showing that large-scale and severe climatic droughts indeed occurred in the years when the river water level dropped at WCR during recent decades, and the historical records at this site would well reflect the climatic droughts of the upper Yangtze in the far past.

A preliminary analysis of historical droughts

The long-term variation in the frequency of RF emergence and the extremely severe droughts that have occurred over the last thousand years can thus be examined by applying this updated chronology (Table 2). Since AD 764, there are totally 84 years of RF emergences, among which 26 years have records of water level below the reference RF. Figure 6 shows long-term change in frequency of RF emergences for each of 50 years (units of occurrences per 50 yr) since AD 951.

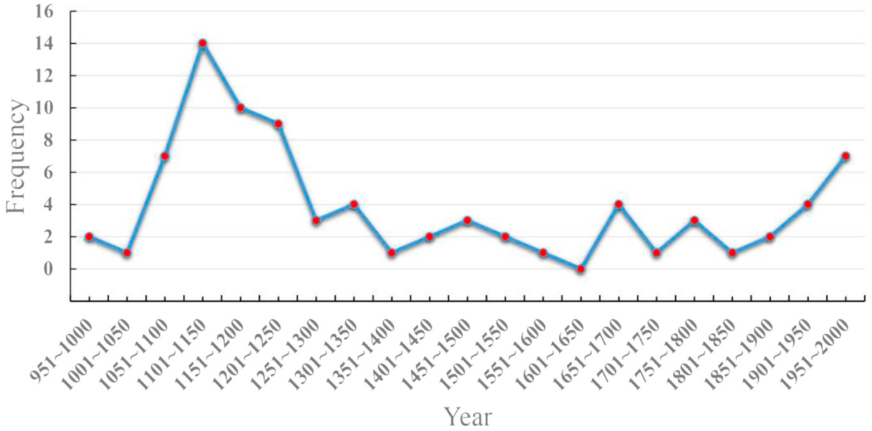


Fig. 6. Frequency (occurrences per 50 yr) of RF emergences for 50-year intervals since AD 951 at White Crane Ridge. Zero value is registered during AD 1601–50.

The preinstrumental change in the frequency of RF emergence may not precisely reflect the variation in the occurrence of drought over the last 1,200 years because the observations and documentation of the RFs may have varied throughout history due to the succession of dynasties and corresponding changes to society. However, the RFs do show a relatively high emergence frequency during AD 1051–1250, a unique paleoclimatic stage known as the Medieval Climate Anomaly (MCA) or Medieval Warm Period (MWP) in the Northern Hemisphere, and a relatively low emergence frequency during the Little Ice Age (LIA) (AD 1501–1900). During AD 1051–1250, the average frequency of RF emergence is 10 times per 50 years. In comparison, the LIA registered an average frequency of only 1.8 times. The highest frequency of low water level events, 14 times, occurred in the 50-year period of AD 1101–50, and the lowest frequency with none occurring during AD 1601–50. It is also interesting to note that there is a new increasing trend of low-water-level events since the mid-nineteenth century.

It is not easy at present to confirm the change in river water level at WCR during the two unique paleoclimatic eras due to the scarcity of high-resolution reconstructions of precipitation or wetness. However, Tan et al. (2018) reported a high-resolution (~4.9 years) stalagmite δ^{18}O record at Shenqi Cave (28°56′N, 103°06′E; 1,407 m MSL) in southwestern Sichuan Province, and showed two most notable wet periods in AD 60–280 and AD 370–510 and decadal-scale droughts in 10 BC–35 AD, AD 740–840, AD 1160–1245, and AD 1550–90. Yin et al. (2010) reported their reconstruction of historical floods in southern Shanxi Province and northeastern Sichuan Province during the 2,200 years. They showed generally less frequent floods AD 900–1350 and more occurrences of floods during the LIA, but a much higher frequency of floods during the twentieth century.

Medieval mega-droughts also occurred in many other regions of the world, including Kenya (Verschuren et al. 2000), Mexico (Cook et al. 2010), Lake Titicaca and Patagonia in South America (Stine 1994), and the western part of the United States (Stine 1994; Cook 2004; Woodhouse and Overpeck 1998; Kleppe et al. 2011), but a wetter climate seemed to prevail in North and Northeast China during this period (Ren 1998; Zhou et al. 2011; Man and Yang 2014). In the Horqin Sandy Land of Northeast China, for example, a wet period was characterized by the abnormal high pollen concentration at Maili peat profile during 1000–660 years BP, with Quercus concentration about 3 times higher than the preceding and afterward periods (Ren 1998). This contrast in precipitation patterns between the Yangtze and northern China has well been recognized in the modern decadal to multidecadal climate variability mode, and it is generally related to the strengthening of the East Asian summer monsoon (EASM) (Jiang et al. 2008; Ding et al. 2009).

A possible mechanism for the contrast of the wetter north and drier Yangtze is sketched in Fig. 7. Due to the general warmth of the Euro-Asian continent, as reported in many previous studies (e.g., Esper et al. 2002; Liu et al. 2005; Ren et al. 2005), the summer thermal difference between the continent and the oceans may have been larger during the MCA (MWP), leading

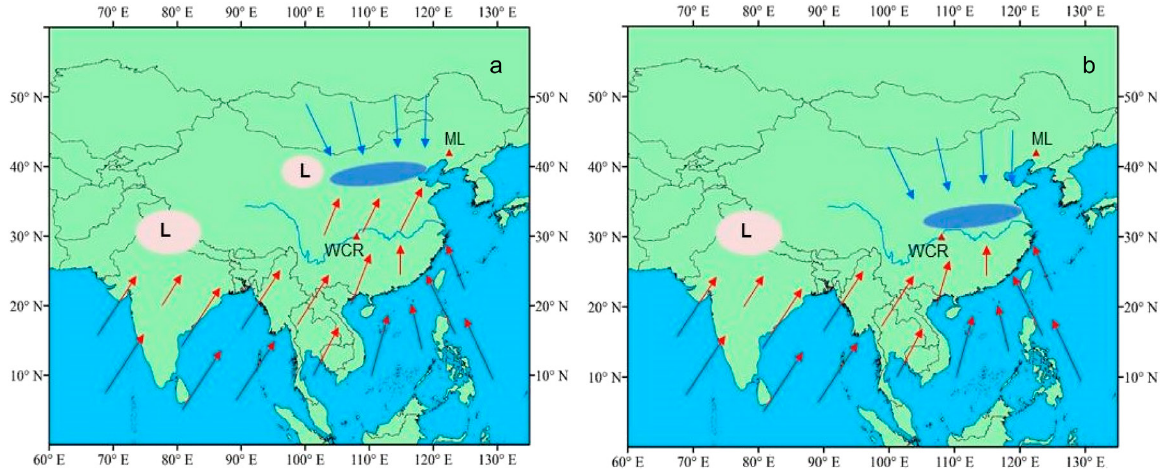


Fig. 7. A sketch of (a) strong and (b) weak East Asian summer monsoon, and the associated positions of the summer main rainfall belt in east China. Blue line is the Yangtze River and "ML" is Maili peat profile in the southern Horqin Sandy Land of Northeast China.

to a broader and lower surface low in the inland and a stronger EASM. The strengthened summer monsoon would bring more moisture and disturbances to the north, resulting in more rains in North and Northeast China and less rains in the mid- to lower Yangtze River.

As seen in Fig. 6, there is no record of the emergence of the RFs in AD 1601–50, which represents the peak of the LIA. This is an extremely unusual phenomenon for the past 12 centuries; it may have been caused by a higher frequency of floods and fewer droughts under the background of generally wetter climatic conditions during this half-century in the mid- and upper Yangtze. In addition, North China experienced unprecedented droughts during this period, particularly during AD 1627–43, which may have triggered peasant uprisings, leading to the replacement of the Ming Dynasty by the Qing Dynasty (Zhang et al. 2006; Zheng et al. 2014). Furthermore, according to the understanding from modern research, the spatial pattern of drought in the north and flooding in the south is usually accompanied by a weakening of the EASM (Fig. 7).

Three extremely low water levels occurred in 1107, 1129, and 1796; among them, 1796 witnessed the lowest water level among all years of RF emergence of approximately 0.65 m below the reference RF corresponding to water levels of approximately 137.4 m MSL at WCR and approximately 136.1 m MSL at QHS. The eight years of RF emergence during the period of instrumental observations had an average annual consecutive 7-day minimum water level of approximately 0.5 m below the reference RF. Therefore, the lowest historical water level observed using the RF was approximately 0.6 m lower than the average annual consecutive 7-day minimum water level before the impoundment of the Three Gorges Reservoir. The drought event would have exerted an enormous impact on the agriculture and society of the upper Yangtze; if such an event were to occur today, the operation of the Three Gorges Reservoir would be severely affected.

In the earlier chronology of RF emergence (Yangtze Valley Planning Office and Chongqing City Museum 1974), AD 1140 was identified as the year with the lowest historical water level (10 chi or approximately 82 cm below the reference RF). Sun (2016) suspected this record, indicating that the figure was inferred from indirect evidence and is therefore unreliable. It is also noteworthy that some records of RF emergence remain to be discovered from the scattered documentation. To deepen our understanding of regional climate change, it is important to uncover additional records to complete the chronology, to confirm the occurrence of major historical drought events by applying other proxy records and to examine the mechanisms and the social impacts of extremely severe droughts.

What caused the low water events to increase anew after the mid-nineteenth century needs to be further investigated. Reliable precipitation records of more than 100 years are lacking for the upper reaches of the Yangtze River. However, annual meteorological droughts indeed increased in frequency in an extended area of southwestern China from the Sichuan Basin to the Yungui Plateau over the last decades (Zou et al. 2010). It may be difficult to associate the modern low water events with variation of the EASM, however, because the weakened EASM of the last decades might have been caused by a different mechanism from that of the preindustrial era due to combined influences of the natural variability, greenhouse gas–induced global warming, and the aerosol-induced regional cooling (Qian et al. 2003; Ding et al. 2009; Zhang et al. 2012).

Conclusions

White Crane Ridge (WCR) is one of the most valuable ancient hydrologic archives in the world. The records of the severe droughts in the upper Yangtze are particularly precious. We updated the historical drought chronology previously developed based on the WCR inscriptions in this paper. The chronology could be used in the future studies of historical climatic and hydrologic droughts. We also made a preliminary analysis of changes of the severe drought frequency during the last thousand years in the upper Yangtze.

It was shown that the droughts occurred more frequently during the Medieval Climate Anomaly (MCA) of Northern Hemisphere, relatively less frequently during the Little Ice Age (LIA), and once again more frequently under the background of modern global warming. It also suggested that a warmer Euro-Asian continent during the MCA was in favor of the stronger East Asian summer monsoon (EASM), and the resulting less precipitation, lower water level, and more frequent and more severe droughts of the Yangtze River, on the centennial scale; on the other hand, a cooler Euro-Asian continent during the LIA would help develop a weaker EASM, and the resulting more precipitation, higher water level, and less frequent and less severe droughts in the Yangtze basin.

Further investigations by using other proxy records are obviously needed to confirm the results in the future. However, the conclusions drawn from the analysis would be of help in understanding the causes and mechanisms of the regional climate change and variability, and also in taking measures in the fields of the Yangtze watershed management to cope with the long-term change in climatic and hydrologic droughts.

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References

Brázdil, R., Z. W. Kundzewicz, and G. Benito, 2006: Historical hydrology for studying flood risk in Europe. *Hydrol. Sci. J.*, **51**, 739–764, https://doi.org/10.1623/hysj.51.5.739.

Cook, E. R., 2004: Long-term aridity changes in the western United States. *Science*, **306**, 1015–1018, https://doi.org/10.1126/science.1102586.

——, R. Seager, R. R. Heim Jr., R. S. Vose, C. Herweijer, and C. Woodhouse, 2010: Megadroughts in North America: Placing IPCC projections of hydroclimatic change in a long-term palaeoclimate context. *J. Quat. Sci.*, **25**, 48–61, https://doi.org/10.1002/jqs.1303.

Ding, Y., Y. Sun, Z. Wang, Y. Zhu, and Y. Song, 2009: Inter-decadal variation of the summer precipitation in China and its association with decreasing Asian summer monsoon. Part II: Possible causes. *Int. J. Climatol.*, **29**, 1926–1944, https://doi.org/10.1002/joc.1759.

Editorial Board, 1993: Appearance of monument Baiheliang from water. Design of Hydroelectric Station, 42 pp.

Esper, J., E. R. Cook, and H. F. Schweingruber, 2002: Low-frequency signals in long tree-ring chronologies for reconstructing past temperature variability. *Science*, **295**, 2250–2253, https://doi.org/10.1126/science.1066208.

Institute of Ancient Documents, 1998: *Complete Collection of the Poetry in Song Dynasty.* Vol. 64, Peking University Press, 621 pp.

Jiang, Z., S. Yang, J. He, J. Li, and J. Liang, 2008: Interdecadal variations of east asian summer monsoon northward propagation and influences on summer precipitation over east China. *Meteor. Atmos. Phys.*, **100**, 101–119, https://doi.org/10.1007/s00703-008-0298-3.

Jones, P. D., and M. Hulme, 1996: Calculating regional climatic time series for temperature and precipitation: Methods and illustrations. *Int. J. Climatol.*, **16**, 361–377, https://doi.org/10.1002/(SICI)1097-0088(199604)16:4<361::AID-JOC53>3.0.CO;2-F.

Kleppe, J. A., D. S. Brothers, G. M. Kent, F. Biondi, and N. W. Driscoll, 2011: Duration and severity of Medieval drought in the Lake Tahoe basin. *Quat. Sci. Rev.*, **30**, 3269–3279, https://doi.org/10.1016/j.quascirev.2011.08.015.

Liu, H., X. Wu, and X. Shao, 1996: A preliminary study on climate change during historical time using image analysis of tree-ring in Kangding area, Sichuan Province. *Geogr. Res.*, **15**, 44–51.

Liu, X., D. H. Qin, X. M. Shao, T. Chen, and J. W. Ren, 2005: Temperature variations recovered from tree-rings in the middle Qilian Mountain over the last millennium. *Sci. China*, **48D**, 521–529, https://doi.org/10.1360/03yd0063.

Man, Z. M., and Y. D. Yang, 2014: Documental evidence of impacts of increased temperature during the Medieval Warm Period on natural environment of eastern China. *Quat. Res.*, **34**, 1197–1203.

Qian, Y., L. R. Leung, S. J. Ghan, and F. Giorgi, 2003: Regional climate effects of aerosols over China: Modeling and observation. *Tellus*, **55B**, 914–934, https://doi.org/10.1046/j.1435-6935.2003.00070.x.

Qiao, S. X., and Z. H. Chen, 1999: The building of chronological tables of carved stone records for low water and flood within upper reaches of the Changjiang River through the age. *Meteor. J. Hubei*, **1999**, 63–71.

Ren, G., 1998: Pollen evidence for increased summer rainfall in the Medieval Warm Period at Maili, Northeast China. *Geophys. Res. Lett.*, **25**, 1931–1934, https://doi.org/10.1029/98GL01508.

Ren, G. Y., and Coauthors, 2005: Recent progress in studies of regional temperature change in China. *Climatic Environ. Res.*, **10**, 701–717.

Stine, S., 1994: Extreme and persistent drought in California and Patagonia during mediaeval time. *Nature*, **369**, 546–549, https://doi.org/10.1038/369546a0.

Sun, H., 2016: The examinations on some issues about the White Crane Ridge inscriptions in Fuling. *Acta Archaeol. Sin.*, **2016**, 49–88.

——, and Y. Y. Chen, 2014: History and value of Bai Heliang's inscription. *Sichuan Cultural Relic*, **2014**, 44–53.

Tan, L. C., and Coauthors, 2018: High resolution monsoon precipitation changes on southeastern Tibetan Plateau over the past 2300 years. *Quat. Sci. Rev.*, **195**, 122–132

Verschuren, D., K. R. Laird, and B. F. Cumming, 2000: Rainfall and drought in equatorial east Africa during the past 1100 years. *Nature*, **403**, 410–414, https://doi.org/10.1038/35000179.

Wang, Y. F., 1996: Ancient water level indicators in Sichuan Province. *Sichuan Water Conservancy*, **5**, 51–54.

——, 1998: Application of the Yangtze Baiheliang inscriptions to scientific and cultural studies. *Sichuan Water Conservancy*, **6**, 50–53.

Woodhouse, C. A., and J. T. Overpeck, 1998: 2000 years of drought variability in the central United States. *Bull. Amer. Meteor. Soc.*, **79**, 2693–2714, https://doi.org/10.1175/1520-0477(1998)079<2693:YODVIT>2.0.CO;2.

Wu, P., L. Wang, and X. Shao, 2008: Reconstruction of summer temperature variation from maximum density of alpine pine during 1917–2002 for west Sichuan Plateau, China. *J. Geogr. Sci.*, **18**, 201–210, https://doi.org/10.1007/s11442-008-0201-7.

Yangtze Valley Planning Office and Chongqing City Museum, 1974: An investigation of historical low flows in Chuan-Yu section of the upper Yangtze River: Special topic of hydro-archaeology. *Culture Relics*, **8**, 76–90, 103–104.

Yi, Z. W., 2003: An ancient hydrologic station of the Yangtze: Fuling Rock Fish. *Quart. J. Yangtze*, **2003**, 91–96.

Yin, S. Y., H. Y. Wang, and D. L. Wang, 2010: Study on historical flood disasters and climate change in the upper reach of the Hanjiang River. *Ganhanqu Yanjiu*, **27**, 522–528.

Zhang, D. D., C. Y. Jim, G. C.-S. Lin, Y.-Q. He, J. J. Wang, and H. F. Lee, 2006: Climatic change, wars and dynastic cycles in China over the last millennium. *Climatic Change*, **76**, 459–477, https://doi.org/10.1007/s10584-005-9024-z.

Zhang, H., and Coauthors, 2012: Simulation of direct radiative forcing of aerosols and their effects on East Asian climate using an interactive AGCM-aerosol coupled system. *Climate Dyn.*, **38**, 1675–1693, https://doi.org/10.1007/s00382-011-1131-0.

Zhang, Q., and Coauthors, 2011: Classification of meteorological drought. *China Stand.*, **5**, 52–55.

Zhang, Z. Y., 1992: Stone tablets in water: Achieves of rock inscriptions at Baiheliang, Fuling. *Sichuan Arch.*, **1992**, 43.

Zheng, J., L. Xiao, X. Fang, Z. Hao, Q. Ge, and B. Li, 2014: How climate change impacted the collapse of the Ming dynasty. *Climatic Change*, **127**, 169–182, https://doi.org/10.1007/s10584-014-1244-7.

Zhou, X., P. Zhao, L. Ge, and T. Zhou, 2011: Characteristics of decadal-centennial-scale changes in East Asian summer monsoon circulation and precipitation during the medieval warm period and little ice age and in the present day. *Chin. Sci. Bull.*, **56**, 3003, https://doi.org/10.1007/s11434-011-4651-4.

Zou, X. K., G. Ren, and Q. Zhang, 2010: Drought variation in China based on a compound index of meteorological drought. *Climatic Environ. Res.*, **15**, 371–378.