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Recent advances on reconstruction of climate and extreme events in China for the past 2000 years

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Abstract: China is distinguished by a prominent monsoonal climate in the east of the country, a continental arid climate in the northwest and a highland cold climate on the Qinghai-Tibet Plateau. Because of the long history of Chinese civilization, there are abundant and well-dated documentary records for climate variation over the whole of the country as well as many natural archives (e.g., tree-rings, ice cores, stalagmites, varved lake sediments and corals) that enable high-resolution paleoclimatic reconstruction. In this paper, we review recent advances in the reconstruction of climate and extreme events over the last 2000 years in China. In the last 10 years, many new reconstructions, based on multi-proxies with wide spatial coverage, have been published in China. These reconstructions enable us to understand the characteristics of climate change across the country as well as the uncertainties of regional reconstructions. Synthesized reconstructed temperature results show that warm intervals over the last 2000 years occurred in AD 1–200, AD 551–760, AD 951–1320, and after AD 1921, and also show that cold intervals were in AD 201–350, AD 441–530, AD 781–950, and AD 1321–1920. Extreme cold winters, seen between 1500 and 1900, were more frequent than those after 1950. The intensity of regional heat waves, in the context of recent global warming, may not in fact exceed natural climate variability seen over the last 2000 years. In the eastern monsoonal region of China, decadal, multi-decadal and centennial oscillations are seen in rainfall variability. While the ensemble mean for drought/flood spatial patterns across all cold periods shows a meridional distribution, there is a tri-pole pattern with respect to droughts south of 25°N, floods between 25° and 30°N, and droughts north of 30°N for all warm periods. Data show that extreme drought events were most frequent in the periods AD 301–400, AD 751–800, AD 1051–1150, AD 1501–1550, and AD 1601–1650, while extreme flood events were frequent in the periods AD 101–150, AD 251–300, AD 951–1000, AD 1701–1750, AD 1801–1850, and AD 1901–1950. Between AD 1551–1600, extreme droughts and flood events occurred frequently. In arid northwest China, climate was characterized by dry conditions in AD 1000–1350, wet conditions in AD 1500–1850, and has tended to be wet over recent decades. On the northeastern Qinghai-Tibet Plateau, centennial-scale oscilla-

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tions in precipitation have occurred over the last 1000 years, interrupted by several multi-decadal-scale severe drought events. Of these, the most severe were in the 1480s and 1710s. In southwest China, extreme droughts as severe as those seen in Sichuan and Chongqing in 2006 are known to have occurred during historical times.

Keywords: high-resolution paleoclimatic reconstruction; extreme events; China; 2000 years

1 Introduction

The study of past climate change enables us to know what has happened in the Earth System, improve our understanding of natural climatic variability, and provide a long-term context for recent climate change (e.g., warming over the 20th century and its hiatus at the start of the 21st century). Data can also be used to assess the relative roles played by natural climate variability in contrast to anthropogenic forcing. Specifically, study of regional climate change over the last 2000 years can provide spatial patterns in variations and various scenarios for measuring the sensitivity and operation of the current climate system (e.g., modulations in internal variability, feedbacks and connections, abrupt changes and regional extreme events) on inter-annual to centennial scales and provide us with knowledge to predict and project climate changes in the near future (PAGES, 2009).

China is characterized by a monsoonal climate in the east, a continental arid climate in the northwest and a cold highland climate on the Qinghai-Tibet Plateau in the southwest. This variety of climate has given rise to a wide range of natural archives (e.g., tree-rings, ice cores, stalagmites, varved lake sediments) that can be used for high-resolution paleoclimatic reconstructions. In addition, the long history of civilization in China also means there are abundant and well-dated documentary records to illustrate the precise sequence of climate change over the last few thousand years and their impacts, especially on humans (Bradley *et al.*, 1993).

In China, the most famous pioneer to study past climate change was Professor Chu Ko-Chen. He critically examined climate-related records from Chinese historical documents and published research papers from the 1920s onwards. One of his major accomplishments was the publication of “a preliminary study on the climatic fluctuations during the past 5000 years in China” that drew on phenological records and evidence for warm and cold events extracted from Chinese historical documents (Chu, 1973). Subsequent to this benchmark study, a nationwide cooperative effort was conducted to extract the enormous number of records of meteorological disasters (e.g., droughts, floods, heat waves, snowstorms, frosts, extreme ice, cold damage) from local gazettes during historical times. As a result of this massive endeavor, a series of ‘dryness and wetness grades’ for 120 sub-regions across China were reconstructed, and a compendium “Yearly Charts of Dryness/Wetness in China for the Last 500-year Period” (CAMS, 1981; Zhang, 1988) was published. In the meantime, weather and climate related information recorded in Chinese classical documents (i.e., Jing, Shi, Zi, Ji in Chinese), the archives of the Qing Dynasty (1644–1911) and the Republic of China (1912–1949), and historical private diaries were also consulted and data was extracted by researchers at the IOGCAS (Institute of Geography, Chinese Academy of Sciences; see Zhang and Gong, 1980; Zhang, 1996). Based on these proxies (e.g., historical weather observations, climate descriptions, records of weather and/or climate-related natural disasters, the impacts of weather and climate anomalies, phenological and biological records), a clear methodology for the study of climate change in historical times was developed (Gong *et al*., 1983). Several key characteristics of Chinese climate change during historical times were studied (Zhang, 1996).

Furthermore, technologies and methods for paleoclimatic reconstruction using available natural archives like tree rings, ice cores, lake sediments, stalagmites and corals were also developed and several laboratories were established. All of these activities led to a series of research works focused on natural, proxy-based, paleoclimatic reconstructions for China (Ye and Lin, 1995). High-resolution proxies, paleoclimatic reconstructions for individual sites (or small areas), and several composite temperature reconstructions for China (e.g., Wang *et al*., 2001; Yang *et al*., 2002; Ge *et al*., 2003; Wang *et al*., 2007) were also achieved; much of these data were indexed in the World Data Center (WDC) for Paleoclimatology Datasets (https://www.ncdc.noaa.gov/data-access/paleoclimatology-data/ datasets), and cited by a number of scientific reports (e.g., IPCC, 2001, 2007; NRC, 2006; EC-CNARCC, 2007) and numerous papers on Northern Hemisphere (NH) or global synthetic temperature reconstructions for the last 2000 years (e.g., Mann and Jones, 2003; Moberg *et al*., 2005; Osborn and Briffa, 2006; Hegerl *et al*., 2007; Mann *et al*., 2008, 2009; Ljungqvist, 2010; Christiansen and Ljungqvist, 2011, 2012; PAGES 2k Consortium, 2013). Highlights of these research activities were summarized in review papers (e.g., Zhang and Crowley, 1989; Wang and Zhang, 1992; Bradley *et al*., 1993; Zhang *et al*., 1997, 1999; Jones and Mann, 2004; Ge *et al*., 2008a; Jones *et al*., 2009), books (e.g., Zhang, 1988; Ye and Chen, 1993; Ye and Lin, 1995; Qin *et al*., 1998), and in a special issue of PAGES News (Wang *et al*., 2005).

In addition to implementing a new phase of the International Geosphere-Biosphere Programme (IGBP) and other research programmes in Global Change over the last 10–15 years, China has also launched two new research themes: the National Key Basic Research Program on Global Change (http://www.most.gov.cn/tpxw/201007/t20100711_78372.htm); and the Strategic Priority Research Program of the Chinese Academy of Sciences on Climate Change (Lu and Ding, 2012). Specially, several novel research projects have focused on climate change in China over the last 2000 years (e.g., Climate Changes in China for the Past 2000 Years: Proxy Data, Variability, Cycle, Abrupt Change and Causes; Forcing and Impacts of the Warm Periods in the Past 2000 Years). Supported by these new research projects, a large volume of high-resolution proxies, paleoclimatic reconstructions, and results have been achieved over the last 10 years. In this paper, we summarize the highlights of recent work.

2 High-resolution and multi-proxy temperature reconstructions

Over the last 10 years, a number of new, high-resolution, temperature reconstructions were reported for China. For example, daily records of snowfall derived from Yu-Xue-Fen-Cun records during the Qing Dynasty (1644–1911) allowed reconstruction of an annual resolution series for winter temperatures since 1736 in eastern China, along the middle-lower reaches of the Yangtze River (25°–34°N, 108°–123°E approximately) (Hao *et al*., 2012), and in southern China (south of ca. 25°N, 106°–120°E) (Ding *et al*., 2015). By using historical records of the dates of first and last frosts extracted from Chinese local gazettes, a temperature series (5-year resolution) for winter half-years (October to the following April) on the North China Plain (ca. 34°–41°N, 105°–123°E) was also reconstructed (Yan *et al*., 2014). Using historical records of abnormal frost dates and snowfalls, as well as the description on plant phenophase in the historical documents, winter half-year temperature series for central eastern China at 10-year (ca. 25°–40°N, east of 105°E) (for AD 220–580; Zheng *et al.*, 2005a) and 20-year (for AD 601–920; Ge *et al.*, 2010a) resolutions were also reconstructed. Winter half-year temperatures for central eastern China over the last 2000 years (first at 30- and then updated to 10-year resolution; Ge *et al.*, 2003; 2013) were reconstructed from more than 1900 historical records of phenological cold/warm events. Moreover, Zhu *et al.* (2009) reconstructed a February-April temperature series for 1750–2002 in northeastern China based on the widths of tree-rings from Korean Pines in the Changbai Mountain area (42.0°–43.5°N, 127.5°–128.5°E), while Chu *et al.* (2011) presented an alkenone-based temperature reconstruction for the growing season over the last 1600 years using varved sediments from Lake Sihailongwan (42.3°N, 126.6°E).

In western China, tree ring-based temperature reconstructions with a duration of more than 300 years have now been conducted at many sites (Table S1 in Supporting Information for locations and references), especially in the Tianshan Mountains, in Xinjiang, and on the Tibetan Plateau. Some of these studies covered up to a millennium (e.g., Wang *et al.*, 2014, 2015; Zhang *et al.*, 2014; Liu *et al.*, 2009; Zhu *et al.*, 2008; Liu *et al.*, 2005, 2007). Moreover, the $\delta^{18}O$ temperature proxy (at a resolution of 10 years) was also derived from ice cores at the following Tibetan Plateau sites: Dunde (38.1°N, 96.4°E); Guliya (37.19°N, 80.68°E); Malan (35.83°N, 90.67°E); Puruogangri (33.92°N, 89.08°E); and Dasuopu (28.38°N, 85.72°E). In addition, a 1600-year-long (AD 350–2010) quantitative reconstruction for yearly summer temperature was inferred from varved sediments in Kusai Lake (35.6°–35.8°N, 92.6–93.3°E) on the northern Qinghai-Tibet Plateau (Liu *et al.*, 2014). Using sediments from Lake Qinghai, Liu *et al.* (2006) presented an alkenone-based temperature reconstruction for 1500 BC to AD 2000 with a resolution of 30–100 years.

These new proxy-based temperature reconstructions provide improved spatial coverage for understanding uncertainties in regional reconstructions and, when synthesized together, enable a high-resolution temperature series for the whole of China over the last millennium. For example, taking 23 proxy-based temperature series from published papers, Ge *et al.* (2010b) assessed uncertainties in temperature reconstructions over the last 2000 years for five Chinese sub-regions. Based on 415 proxies (including 373 from tree rings mostly less than 1000 years old), Shi *et al.* (2012) built a preliminary temperature reconstruction for China over the last millennium using a modified point-by-point regression (PPR) approach. More specifically, by synthesizing high-confidence regional temperature signals from 28 proxies (with high quality reconstructions) from the whole of China, Ge *et al.* (2013) reconstructed a new 2000-year temperature series at a resolution of 10 years (Figure 1) using partial least squares (PLS) and principal component regression (PCR) analyses. Results of this study show that warm intervals over the last 2000 years were in AD 1–200, AD 551–760, AD 951–1320, and after AD 1921, while cold intervals were in AD 201–350, AD 441–530, AD 781–950, and AD 1321–1920. Interestingly, temperatures during AD 981–1100 and AD 1201–1270 were comparable to those of our Present Warm Period, but have an uncertainty of 0.28°–0.42°C at 95% confidence level. Temperature variations over the whole of China are typically in phase with those of the Northern Hemisphere (NH) after AD 1000, the period which covers the Medieval Climate Anomaly, the Little Ice Age (LIA), and the Present Warm Period. In contrast, a warm period found to occur in China during AD 541–740 was not as obvious as in the NH.

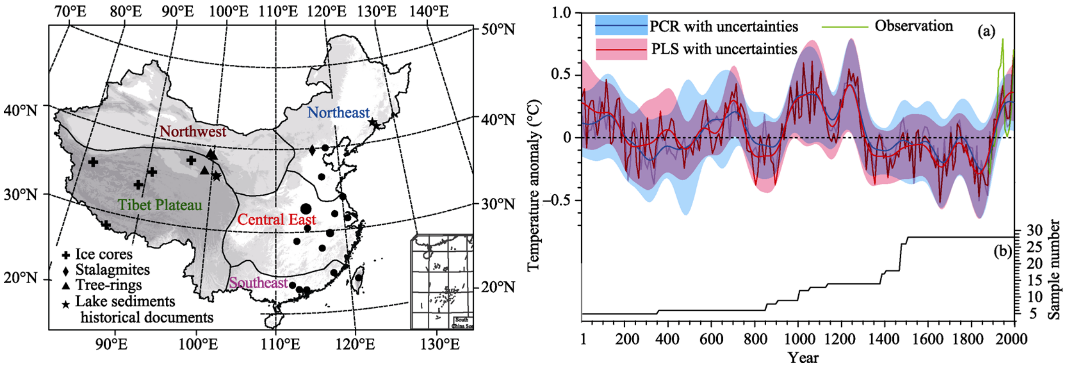

Figure 1 Locations and types of 28 temperature proxies (left panel), and temperature reconstructions for China (a in right panel; Ge *et al*., 2013) based on 28 temperature proxies with PLS (red lines) and PCR (blue lines) methods respectively at decadal (thin lines) and centennial timescales (solid lines; smoothed by a 5-point FFT filter), along with the 95% confidence level (shading). The reference value is the mean temperature from 1851 to 1950. The green line indicates the observed average air temperature. (b) Numbers of temperature proxies used.

Analysis of the rate of temperature change over the last 2000 years shows that, at a 100-year scale, the warming rate for the whole of China in the 20th century was only 0.6°C/100 a, while the peak warming rate for the period from the LIA to the 20th century reached 1.1°C /100 a, which was the greatest one in the past 500 years and probably over the last 2000 years. On a 30-year timescale, warming in the 20th century is quite notable, but the peak rate is still lower than those seen in previous periods, including rapid warming from the LIA to the 20th century and from AD 270s–290s to AD 300s–320s. The exact timing, duration and magnitude of these warming peaks vary from region to region at all scales, while the peak rates on a 100-year scale in AD 180–350 in northeastern China, in AD 260–410 and AD 500–660 in Tibet were all greater than those seen from the mid-19th to 20th centuries. It is also worth noting that the most rapid cooling rates (at scales of 30 to 100 years) in the LIA were high, but not unprecedented for the last 2000 years (Ge *et al*., 2011a).

3 Reconstructions of precipitation and rainfall variability

Among the many historical documents in China, Yu-Xue-Fen-Cun records are a unique direct source for quantitative precipitation reconstruction at high-resolution in the monsoonal region of China. These records contain measurements of both snow depth after each snowfall and infiltration depth after each rainfall in units of Fen (0.32 cm) and Cun (10 Fens = 3.2 cm), as well as records of rainy and snowy days and accurate descriptions of precipitation over given periods (e.g., one dekad, one month or one season; Ge *et al*., 2005). Based on these unique records, Zheng *et al*. (2005b) were able to reconstruct seasonal precipitation since 1736 at 17 stations along the middle and lower reaches of the Yellow River as well as variations in the rainy season driven by the East Asian Summer Monsoon over the last 300 years. Ding *et al*. (2014) reconstructed a starting-date series for the pre-summer rainy season in South China (i.e., the first stage of the Asian summer monsoon rainband in China) while Ge *et al*. (2008b) reconstructed a time-series (including start and end dates) and precipitation amount for Meiyu (the second stage of the Asian summer monsoon rainband in China) in the middle-to-lower reaches of the Yangtze River. Wang *et al*. (2008) and Ge *et al*. (2011b) reconstructed series of start and end dates for the rainy season on the North China Plain and on the northern edge of the monsoonal area (i.e., the last stage of the Asian summer monsoon rainband in China).

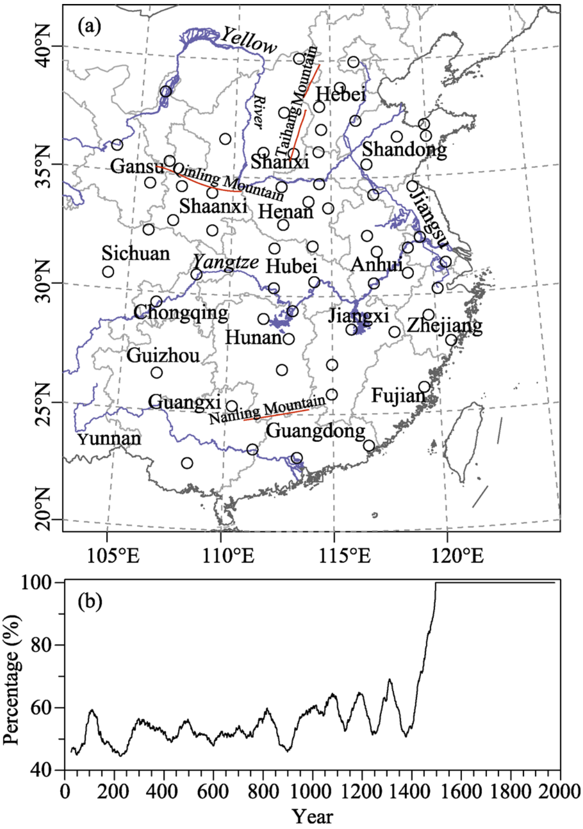

Figure 2 Locations of 63 sites in the dataset of yearly drought/flood grade derived from Chinese historical documents starting from 137 BC (a) and percentage of available data for each drought/flood grade, excluding grade 3 (b)

Based on descriptions of drought and flood-related disasters (i.e., events that had direct impacts on agriculture and society) extracted from Chinese historical documents, Zhang (1996) developed a dataset to describe a yearly drought/flood grade since 137 BC for 63 sites (Figure 2a) in eastern China. The grades in this dataset were classified using the ideal frequency criteria of 10% (grade 1, severe drought), 20% (grade 2, drought), 40% (grade 3, normal), 20% (grade 4, flood), and 10% (grade 5, heavy flood) for the whole area across this period, calibrated by considering the intensity, duration, and area of disasters and their impacts. However, these data are only partially available before 1470 as fewer historical documents survive from earlier times (Figure 2b), and, in addition, data for the grade of a drought or flood are unevenly distributed spatially (e.g., very few data are available on the grade of a drought or flood in China before AD 760 and even fewer data south of the Huaihe River at ca. 34°N before AD 300; Zhang, 1996). Nevertheless, by using this grade dataset, Zheng *et al*. (2006) were able to develop a method to define a long-term pattern in precipitation change (with a regional dry/wet index) and reconstructed a regional dry/wet index series for the North China Plain (ca. 34°–40°N, east of 105°E), the Jiang-Huai area (ca. 31°–34°N, east of 110°E), and the Jiang-Nan area (ca. 25°–31°N, east of 110°E) for the last 1500 years. The effect of missing data on the homogeneity of these reconstructions was detrended using a polynomial fit to changing trend in the number of records and, recently, these reconstructions (Figure 3) have been extended back to 2000 years (Zheng *et al*., 2014a). This series thus provides a unique proxy for studying long-term patterns and regional differences in rainfall over the monsoonal area of China (Shen *et al*., 2009).

Tree-ring is one of the important proxies for reconstructing precipitation and drought variability in western China, as this region has an arid to semi-arid climate. Over the last 10 years, around 30 reconstructions based on more than 130 tree ring chronologies (Table S2 in Supporting Information for locations and references) reported precipitation or drought indices (e.g., the Palmer drought severity index; the standardized precipitation evapotranspiration index) at yearly resolution. For the northeastern part of the Tibetan Plateau, eight reconstructions are available for the last 1000 years (e.g., Gou *et al*., 2015a; Wang *et al*., 2013; Zhang *et al*., 2011a; Shi *et al*., 2009; Liu *et al*., 2006; Shao *et al*., 2005, 2006; Zhang *et al*., 2003), of which, the longest two extend back more than 3000 years (Shao *et al*., 2010; Yang *et al*., 2014a). In addition, several high resolution (annual to decadal) proxy series for precipitation or Asian summer monsoon variability were derived from stalagmites (e.g., He *et al*., 2005; Hu *et al*., 2008; Cosford *et al*., 2008; Zhang *et al*., 2008; Tan *et al*., 2009; 2011; Cui *et al*., 2012; Zhao *et al*., 2015), and lake sediments (e.g., Bird *et al*., 2014; Liu *et al*., 2011). All of these proxy series dated back more than 1000 years.

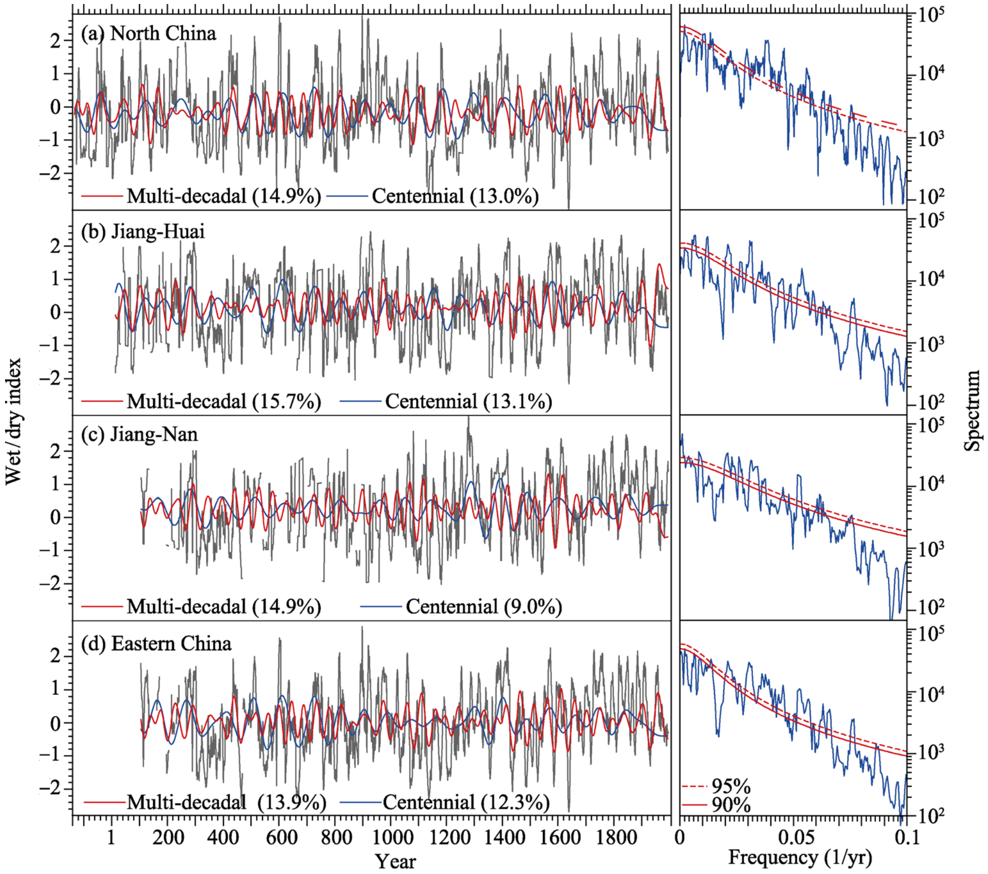

Figure 3 Regional dry/wet index series for the North China Plain (a), Jiang-Huai area (b), Jiang-Nan area (c), and central eastern China (d) for the past 2000 years derived from yearly drought/flood grade dataset after detrending the effect of data missing on the homogeneity (Ge *et al*., 2014). The blue and red lines show the variations of regional dry/wet index at multi-decadal (40–75 years) and centennial (80–150 years) scale respectively, with the value of explained variance in brackets. Right panel: Results of spectral estimation for the regional dry/wet index series using the Multi-Taper Method.

The above reconstructions provided new proxies to study the characteristics on precipitation change in China over the past 2000 years. Results of multi-taper spectral analyses on reconstructions for the North China Plain, the Jiang-Huai area, and the Jiang-Nan area all show that there were decadal, multi-decadal and centennial oscillations in rainfall variability in the monsoonal region of China (Figure 3). Within this variation, a number of significant cycles were detected: 90–100a, 70–80a, 43–48a, 35a, 25–27a, and 17–18a on the North China Plain; 90–100a, 73–75a, 63–68a, 55a, 45a, 37a, and 26a in the Jiang-Huai area; and 85–100a, 75–77a, 58–65a, 37–39a, 31a and 26a in the Jiang-Nan area (Ge *et al*., 2014). Significant cycles with 70–80a and 20–30a were also found in precipitation reconstructions for the middle-lower reaches of the Yellow and Yangtze rivers (Hao *et al*, 2008, Ge *et al*., 2008b), although there was inconsistent phase for decadal, multi-decadal and centennial dry/wet variation on the North China Plain, and in the Jiang-Huai Jiang-Nan areas (Zheng *et al*., 2006; Hao *et al*., 2009; Shen *et al*., 2009).

Reconstruction of spatial patterns shows that there has been no fixed relationship in precipitation anomalies during either the five centennial-scale cold (AD 440–540, AD 780–920, AD 1390–1460, AD 1600–1700, and AD 1800–1900) or four warm (AD 650–750, AD 1000–1100, AD 1190–1290, and AD 1900–2000) periods in eastern China over the last 2000 years (Hao *et al*., 2016). Nevertheless, the ensemble mean of the drought/flood spatial pattern for all five cold periods does show an east-to-west distribution (Figure 4), with floods east of 115°E and droughts west of 115°E (with the exception of one flood between 110°E and 105°E). For most warm periods, droughts dominate north of the Yangtze River, while floods are more common to the south; the ensemble mean of the drought/flood spatial pattern for all four warm periods shows a tri-pole pattern with droughts south of 25°N, floods prevalent between 25°–30°N, and droughts north of 30°N (with the exception of one flood on the Loess Plateau; Zheng *et al*., 2014b). Results also show that the observed increase in frequency over the last two decades of a drought-in-the-north/flood-in-the-south spatial pattern in eastern China is unusual for the last five centuries (Shen *et al*., 2009).

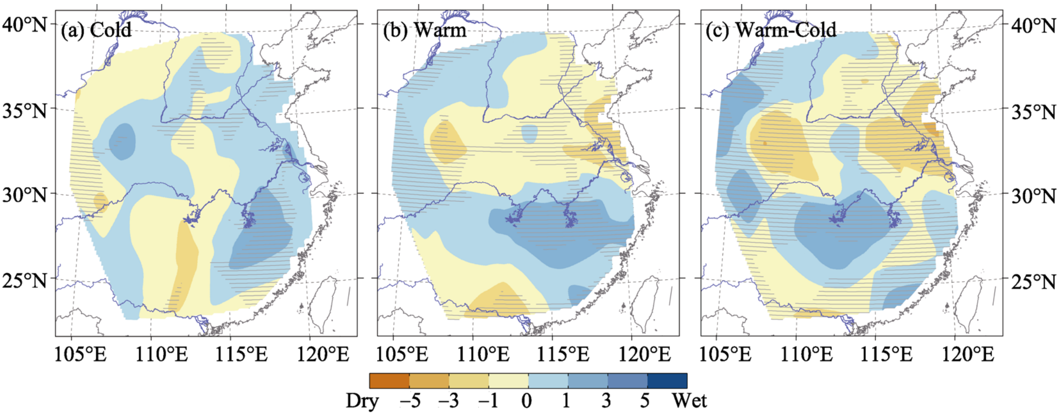

Figure 4 Spatial patterns of droughts and floods in eastern China in cold and warm periods over a centennial scale (Hao *et al*., 2016). (a) Ensemble mean for all five cold periods (AD 440–540, 780–920, 1390–1460, 1600–1700, 1800–1900). (b) Ensemble mean for all four warm periods (AD 650–750, 1000–1100, 1190–1290, 1900–2000). (c) Difference between warm and cold periods (warm minus cold). The shaded area is the 90% significance level based on a chi-square test.

Chen *et al*. (2010) reviewed spatial and temporal patterns in effective moisture variation as revealed by different proxies from 17 records across arid Central Asia (a region extending from the Caspian Sea in the west to the modern Asian summer monsoon limit in the east, encompassing the Central Asian countries, northwestern China, and the southern Mongolian Plateau). The authors synthesized a reconstruction at a decadal resolution for moisture variation over the last 1000 years, using five of the 17 available records selected on the basis of reliable chronologies and robust proxies. The high- and low-resolution data recovered by this study all showed that, over the last 1000 years, the climate in arid Central Asia was characterized by a relatively dry period AD 1000–1350, a wet period AD 1500–1850, and tended to be moist in recent decades. Over the last 1000 years, multi-centennial moisture changes in arid Central Asia showed a generally inverse relationship with respect to temperature changes in the Northern Hemisphere, China, and in western Central Asia. This change in moisture history in arid Central Asia also showed an out-of-phase relationship with that seen in monsoonal Asia (Chen *et al.*, 2010). While in the southeast of arid Central Asia, from the northeastern Qinghai-Tibet Plateau to the western margins of the Qinling Mountains, reconstructions from both tree rings (Shao *et al.*, 2010; Yang *et al.*, 2014a) and stalagmites (Zhang *et al.*, 2008) showed that there were centennial-scale oscillations in precipitation over the last 1000 years. These were interrupted by several multi-decadal severe drought events, including two prominent droughts in the 1480s and the 1710s (Shao *et al.*, 2010; Yang *et al.*, 2014a). A 3500-year tree-ring-based precipitation reconstruction for the northeastern Tibetan Plateau (Figure 5) showed that moisture conditions over recent decades were the wettest recorded. Notable historical dry periods occurred in the 4th century and in the second half of the 15th century; the driest individual year (since 1500 BC) was 1048 BC, while the wettest was 2010. Precipitation variability on the northeastern Tibetan Plateau appeared not to be associated with inferred changes in the intensity of the Asian monsoon during recent millennia (Yang *et al.*, 2014a).

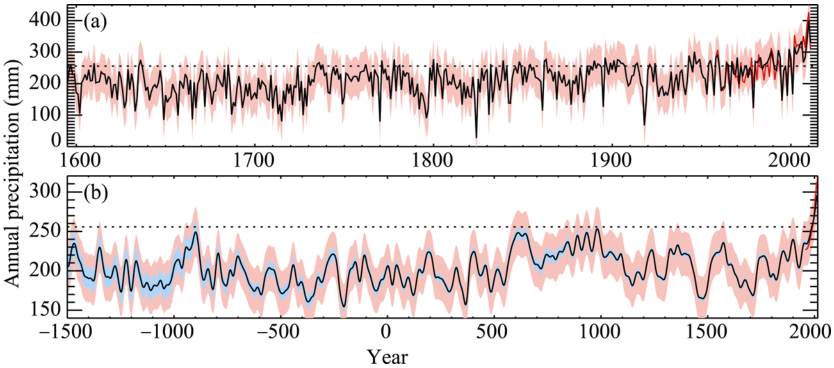

Figure 5 Tree ring based reconstruction for annual precipitation on the northeastern Tibetan Plateau (Yang *et al.*, 2014a). (a) Annual precipitation from 1595 to 2011, together with total uncertainty (pale red), the part of this uncertainty that arises from chronology (pale blue), and the observed regional precipitation since 1957 (red). The horizontal dotted line indicates the mean precipitation over the calibration period (1957–2011). Note that the calibration residuals show that the estimated values somewhat exaggerate dryness in some dry years (e.g., 1978 and 1998), and this should be borne in mind when interpreting extremely dry years in the reconstruction. (b) As in (a), except that data are shown for the period since BC 1500 with 50a smoothing (smoothed values will be more uncertain near the end of the time series).

4 Extreme climate events reconstructions

4.1 Extremely cold winters and burning hot summers

Regional historical climate reconstructions may help us to place recently observed extreme climate events into the context of much longer timespans; by doing this, we can understand whether the recent climate is actually more extreme than it has been in the past, which is a current hot topic in China (Zheng *et al.*, 2014c). For example, Zheng *et al.* (2012) defined extremely cold winter events as those that have a probability of occurrence lower than the 10th percentile of a probability density function, based on observed winter temperatures since 1951 in southern China. On this basis, they created a series of impact severity levels using documented evidence of events between 1951 and 2000, and evaluated three indexes for the freezing of rivers and lakes, widespread snow and ice storms, and cold damage to subtropical or tropical crops. Using these criteria, they identified 50 extremely cold winters for the period 1650–1949 based on 4000 pieces of comparable information extracted from local gazettes in southern China. Data were verified using data from three weather stations with long records and led to the conclusions that the most frequent extremely cold winter events occurred during AD 1650–1699 and in the first and second half of the 19th century, when frequencies were twice as high as in the second half of the 20th century. In contrast, frequencies of extremely cold winters during the 18th century were close to those seen in the second half of the 20th century. The high frequencies of extremely cold winters observed in AD 1650–1720 and AD 1795–1835 were likely due to the Maunder and Dalton Minimum. Indeed, the intensities of some historically cold events, such as those in the winters of 1654, 1670, 1690, 1861, 1892 and 1929, exceeded those of the coldest winters since 1951. Hao *et al.* (2011) identified historical analogues of the central and southern Chinese 2008 extreme snow event (ESE) from the chronology of extremely cold winters reconstructed over the last 500 years comparing geographical coverage with days of snowfall (greater than 15 days), snow/icing-cover (greater than 20 days), and total accumulated snow depth (greater than 30 cm for a single winter) and found that there were 25 annual ESEs over the past 500 years (Table 1) comparable to the winter of 2008 in snowfall days, snow cover/icing days, and snow depth. These ESEs, however, exhibited a variable spatial pattern and only those that occurred in the winters of 1578, 1620, 1796 and 1841 (probability of occurrence: once every 100 years) had comparable snowfall pattern to 2008. Comparisons between occurrences of ESEs and long-term temperature changes showed that ESEs analogous to that seen in 2008 all occurred in a relatively warm phase that was soon followed by a cooling phase (Hao *et al.*, 2011).

Zhang and Gaston (2004) reported 19 extreme burning hot summers in the last 1000 years by surveying weather and related impact records from “A Compendium of Chinese Meteorological Records of the Last 3000 years” (Zhang, 2004). Summers were defined as burning hot if high temperatures were recorded in more than three provinces; results showed that the northern China heat wave in summer 1743 was the greatest in intensity, injuries, area of coverage and duration. During this event, the daily maximum temperature reached 44.4°C in Beijing in July 1743, as observed by Father Gaubil using a Réaumur-scale thermometer (Table 1), which passed the highest records (June and July of 1942, July of 1999) observed in the 20th century. It is implicated that the intensity of regional heat wave occurred in the context of recent global warming may not exceed the natural climate variability during the historical times.

4.2 Extreme drought and flood

Based on a yearly dataset of drought and flood grades for 63 sites (Figure 2a) across eastern

Table 1 Historical extreme snowfall events (ESEs) comparable to 2008, including duration (period over which a high incidence of heavy snowfall occurred), days of snowfall, snow cover or icing, and snow depth (ranges given because of geographical variability between sites, "?" means no data available) (Hao *et al*., 2011).

Winter	Duration of heavy snowfall event (dd/mm)	Days in disaster area		Snow depth (cm)		Spatial pattern*
		snowfall	snow cover/icing	mean	Max. record	
1578-79	29/11-01/02	>20	>30	>30	>100	III
1620-21	15/12-20/02	15–30	>30	30–50	>60	III
1654-55	21/12-05/02	15–40	20–40	40–50	>60	Ib
1660-61	04/12-29/01	?	>30	?	?	Ic
1665-66	01/01-02/02	?	>30	?	?	Ic
1670-71	15/12-05/02	>15	>30	30–50	>100	Ia
1676-77	10/12-01/02	?	>30	>50	>100	Ic
1683-84	28/12-12/02	?	>30	30–50	>60	Ia
1689-90	28/12/-15/01	?	>30	?	>60	Ic
1690-91	21/12-15/02	>15	>30	30–60	>100	Ia
1694-95	17/12-10/03	?	>30	?	?	II
1700-01	10/12-10/02	?	>20	?	>100	Ia
1714-15	06/01-03/02	>15	>30	>30	>50	Ib
1719-20	01/02-08/03	?	>20	>30	>60	Ib
1796-97	29/12-30/01	15–25	20–30	30–40	>50	III
1830-31	10/01-23/02	15–25	15–40	30–40	>50	Ic
1831-32	14/12-07/02	15–30	25–50	30–50	>100	Ia
1832-33	19/01-20/02	15–20	20–35	30–50	>90	Ia
1840-41	18/12-01/02	15–20	25–40	30–50	>100	Ic
1841-42	09/12-10/01	15–30	25–50	≈50	>100	III
1877-78	30/12-09/02	≈15	20–50	>30	>45	Ia
1887-88	13/01-13/02	≈15	20–35	30–40	>90	II
1892-93	04-06/01,13-30/01, 25/01-02/02	≈15	>25	30–50	>90	Ia
1929-30	16/12-25/02	>15	>25	30–40	>60	II
1930-31	20/12-20/02	>15	>25	30–40	>60	II
2007-08	10-16/01,18-22/01, 25-29/01, 31/01-02/02	12–17	15–25	30–35	50	III

*Spatial patterns: pattern I, a snow front moving from the north to the south of China, including pattern Ia, continuous snowfall over most of eastern China; pattern Ib, an ESE approximately on the east coast of China; pattern Ic, heavy snow over scattered regions of eastern China, with cold dry conditions for the whole of this region; pattern II, continuous snowfall over southern China (from the Huaihe River to the southern border); pattern III, persistent snowfall in the region between the Yellow River and Nanling Mountain.

Table 2 Temperature observations for each day in Beijing at 15:30 pm between the 20th and 26th of July 1743 by Father Gaubil using a Réaumur-scale thermometer (°R), their equivalents in Celsius (°C), and comparisons with the highest records from the 20th century (Zhang and Gaston, 2004).

Date	1743-07-20	1743-07-21	1743-07-22	1743-07-23	1743-07-24	1743-07-25
Temperature (°R)	33.25	33.25	34.00	34.00	34.25	35.25
Temperature (°C)	41.6	41.6	42.5	42.5	43.1	44.4

Statistical features of the 1743 heat wave vs. highest recorded temperatures in the 20th century				
Month heat wave occurred	July 1743	June 1942	July 1942	July 1999
Maximum temperature (°C)	>44.4*	42.6	40.0	42.2
Days of >40°C	6	3	3	1
Successive days of >38°C	6	3	3	2

* Only the 15:30 pm observation is used.

China since 137 BC and the regional dry/wet index series (Figure 3), Hao *et al*. (2010a) reconstructed the chronology of extreme drought and flood events on the North China Plain, in the Jiang-Huai and Jiang-Nan areas, and in central eastern China over the last 2000 years. Although these events can be identified by drought/flood grade criteria, hit-area and regional dry/wet index, this is equivalent to the occurrence probabilities of drought/flood and within the 10th percentile of a probability density function, as derived from instrumental precipitation observations in China since 1951. Results show that there were 227 extreme droughts and 190 extreme floods in the period 137 BC to AD 2000 on the North China Plain and that six extreme droughts and four extreme floods occurred between 1951 and 2000. Although data is missing for yearly drought/flood grades in the Jiang-Huai and Jiang-Nan areas before AD 1470, it is clear that there were 142 extreme droughts and 174 extreme floods between AD 10 and 2000 in the Jiang-Huai area. Of these, five extreme droughts and six extreme floods occurred within the period 1951–2000. In the Jiang-Nan area, 127 extreme droughts and 159 extreme floods occurred between AD 100 and 2000 and, of these, four extreme droughts and five extreme floods occurred between 1951 and 2000. In central eastern China, there were 209 extreme droughts and 195 extreme floods (including 23 coincident extreme drought and flood events) between AD 100 and 2000, of which four extreme droughts, four extreme floods, and one coincident event occurred between 1951 and 2000. Observed changes in the occurrences of extreme events (Figure 6) show that in the eastern monsoonal region of China, extreme droughts were more frequent in the periods AD 301–400, AD 751–800, AD 1051–1150, AD 1501–1550, and AD 1601–1650. In this region, extreme floods were more frequent in the periods AD 101–150, AD 251–300, AD 951–1000, AD 1701–1750, AD 1801–1850, and AD 1901–1950, while during 1551–1600, coexisting extreme drought and extreme flood events occurred most frequently.

Based on a dataset of dryness and wetness grades for 120 Chinese sub-regions (CAMS, 1981; extended by Zhang *et al*., 2003) and by considering intensity, duration, and spatial coverage, Shen *et al*. (2007) investigated the exceptional drought events (i.e., extended over a prolonged period; affecting an extended area) that were seen in eastern China in the last five centuries. In this study, they identified three exceptional drought events, 1586–1589, 1638–1641, and 1965–1966. These were the most severe droughts of the last five centuries seen in eastern China; more than 40% of the region was affected while the drought center experienced a significant reduction in summer rainfall (ca. 50% or more). These three extreme droughts all developed first in the north of China (34°–40°N), and then either expanded southwards or moved down the Yangtze River valley (27°–34°N) to northern part of the southeastern coastal area (22°–27°N). In 1965–1966, a significant reduction in summer precipitation was caused by a weakening of the summer monsoon and an anomalous westward and northward displacement of the western Pacific subtropical high. Indeed, all three of these exceptional drought events may be triggered by large volcanic eruptions and amplified both by volcanic activities and El Niño events. Hao *et al*. (2010b) also investigated the spatial pattern and temporal evolution of the prolonged severe drought of 1876–1878, using a seasonal precipitation reconstruction from 17 stations within the middle and lower reaches of the Yellow River recorded in Yu-Xue-Fen-Cun records since 1736. Results of this study indicate that this prolonged severe drought started in the spring of 1876 and did not stop until the spring of 1878, which was the most severe and extreme drought in northern China in the last 300 years. Indeed, within the three-year drought period, harvest failures raised the price of rice 5–10 times higher than in a normal year and population of the five provinces of northern China decreased by more than 20 million because of death and migration. Subsequent related investigations suggested that this 1876–1878 drought could be linked to abnormally high sea surface temperatures (SST) in the equatorial central and eastern Pacific, a strong El Niño episode, and positive Antarctic Oscillation (AAO) anomalies.

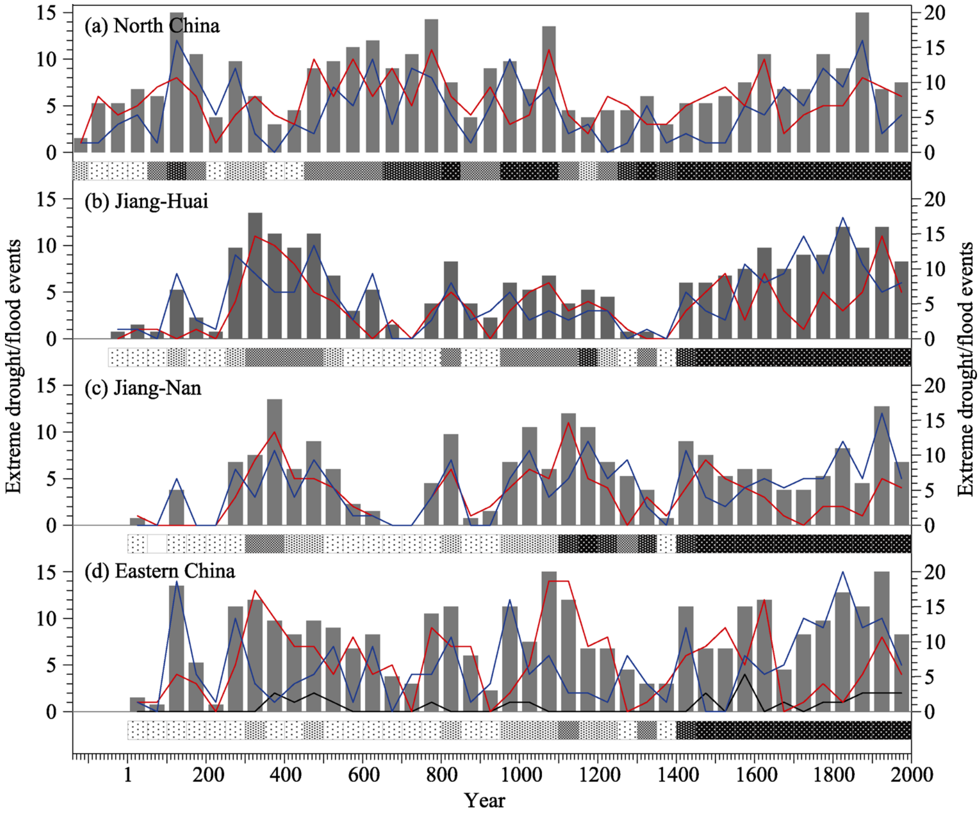

Figure 6 Changes in the frequency of extreme drought and flood events for each 50-year period in eastern China over the last 2000 years (Hao *et al*., 2010a). Red line: extreme drought; blue line: extreme flood; black line: coexisting drought and flood; grey bar: total of extreme drought and flood events. The cross bars below each plate indicate confidence levels of results for every 50 years, which marked with different levels of A (full confidence), B (very high confidence), C (high confidence), D (medium confidence), and E (low confidence), and the periods with scarce data were marked with blank.

Based on a network of tree-ring chronologies, Cook *et al*. (2010) presented the Monsoon Asia Drought Atlas (MADA), a seasonally resolved gridded spatial reconstruction of Asian monsoon droughts and pluvials over the last 1000 years. Their results show that megadroughts, such as those that occurred in the periods 1638–1641 in China, 1756–1768 in southern Asia, 1790 and 1792–1796 in East India, and 1876–1878 in North China and southern Asia, are closely linked to large-scale anomalous patterns of tropical Indo-Pacific SSTs. However, it is also worth noting that comparisons between the MADA and a dataset of dryness/wetness grade for 120 sub-regions of China derived from historical documents (CAMS, 1981) indicate that atlas data alone cannot effectively represent dryness and wetness in eastern China, probably because of the lack of tree-ring proxy records in this region for the MADA (Yang *et al*., 2013).

In the arid and semi-arid zones of northwestern China, lots of case studies identified periods of extreme drought in individual area based on tree-ring-based precipitation or PDSI reconstructions. For example, Li *et al*. (2006) investigated the occurrence of extreme drought events using tree-ring-based April-June PDSI reconstruction for the period 1675–2002 in the central Tianshan area (ca. 40°–45°N, 83°–93°E) of Xinjiang (the northwest frontier). They found evidence for just one extreme drought year (1690) between 1675 and 1699 and no extreme droughts in the period 1700–1799. However, more frequent extreme drought years were seen in the period 1800–1950 (e.g., 1823, 1843, 1885, 1895, 1900, 1910, 1916–1919 and 1943–1945) and a clear trend in increasing moisture intensity was seen in the second half of the 20th century. Zhang *et al*. (2011b) identified severe and extreme droughts between 1700 and 2005 over the whole Qilian Mountains area (36°–40°N, 93°–103°E approximately) using a tree-ring network of 12 chronologies. They also found that severe and extreme drought events became more frequent during the 20th century; one multi-year event recorded during the late 1920s to the early 1930s was the longest within the period 1700–2005. In contrast to this work, Gou *et al*. (2015b) presented an 850-year (AD 1161–2010) reconstruction for May-July self-calibrating PDSI in the western Qilian Mountains (37.5°–40.0°N, 95°–100°E) based on two almost 1000 years Qilian Juniper ring-width chronologies (ca. 39.7°N, 98.8°E) and the result showed that the most extreme drought years were 1261, 1258, 1495, 1323, 1198, 1505, 1693, 1290, 1962, 1714, 1342, 1660 and 1721 (in order of intensity). Gou *et al*. (2015b) also provided evidence for three prolonged periods of drought encompassing more frequent, severe and extreme drought years (the periods AD 1260s–1340s, 1430s–1540s, and 1640s–1740s) that coincided with periods of Wolf, Spörer and Maunder Minimum. Liu *et al*. (2013) also identified an extreme drought year in the east of the Qilian Mountains using a tree-ring-based precipitation reconstruction for Mount Xinglong (35.6°–36°N, 103.8°–104.2°E) since AD 1679. The longest dry interval in this region was the period 1811–1870, while the most severe drought period was 1924–1929. There were six extreme drought years in this region in the 18th and 19th centuries and six droughts between 1901 and 1950.

Based on a 2850-year (from 843 BC onwards) tree-ring width composite chronology using archaeological wood samples from 13 sites and living tree samples from seven sites, Shao *et al*. (2010) reported that over the last 2000 years, there were extreme drought periods in decades of the 360s, 490s, 690s, 1150s, 1290s, 1480s, and 1710s on the northeastern Qinghai-Tibet Plateau (ca. 36°–39°N, 96°–100°E). Yang *et al*. (2014b) also investigated drought variability on the northern fringes of the Asian summer monsoonal region (ca. 34°–43°N, 95°–112°E, the region including the Qilian Mountains, the Hexi Corridor and the Great Bend of the Yellow River) using tree rings, historical documents and instrument data. Their results show that variations in droughts were roughly consistent over the study area on decadal-to-centennial timescales and that dry periods with more frequent extreme drought events since AD 1450 were in 1480–1499, 1575–1590, 1625–1644, 1710–1729, 1875–1878 and 1922–1931. In addition, tree-ring based PDSI reconstruction for the southeastern Tibetan Plateau (ca. 27°–30°N, 97°–100°E) between 1440 and 2007 shows that the extreme drought years were in 1444, 1447, 1452, 1454,1455, 1456, 1466, 1502, 1552, 1567, 1576, 1684, 1736, 1823, 1897, 1943, and 2001 and that extremely dry decades were in the periods 1440s–1460s, 1560s–1580s, 1700s, 1770s, 1810s, 1860s and 1980s (Fang *et al.*, 2010).

In the southwestern part of China, extreme drought events seem to be occurring more frequently since 2006 and include the most extreme example on record, the period between late-spring and summer 2006 around Chongqing and Sichuan, as well as the most extreme prolonged example (August 2009 to June 2010). Indeed, successive severe drought events between spring 2009 and 2013 (Qin, 2015) in this region of China have promoted a number of studies on their long-term effects. For example, Hao *et al.* (2007) investigated the history of severe droughts in Chongqing and the surrounding area over the last 1000 years using data derived from historical documents (i.e., duration, impact intensity, and hit-area) and found that events equivalent to the extreme drought of 2006 in fact occurred several times before the 21st century (e.g., in 1939, 1877, 1811, 1649, and 1648). Moreover, a tree-ring based PDSI reconstruction for spring in the period between 1650–2011 showed that extreme drought events also occurred in 1736–1737, 1758, 1762, 1766, 1768–1769, 1819, 1969, and 2008 in Lijiang, Yunnan Province (Bi *et al.*, 2015). A winter (October to January) PDSI reconstruction derived using tree-ring data from Gaoligong Mountain (in northwestern Yunnan Province) for the period 1795–2004 showed that extreme drought years in this region were in 1813, 1816, 1822, 1861, 1864–1865, 1907, 1909, 1980, 1987, and 1995–1996 (Li *et al.*, 2011). In addition, a tree-ring based PDSI reconstruction for spring in the central Hengduan Mountains (the area linking the southwest of China to the Tibetan Plateau) showed that extreme drought events within the period 1655–2005 also occurred in 1670, 1706, 1735–1736, 1757, 1766, 1772, 1792, 1800, 1820, 1870, 1887, 1897, 1987, and in 1999 (Fan *et al.*, 2008). These results suggest that, at least in the southwest of China, the extreme droughts of the 21st century are not more intense than those seen in historical times.

5 Conclusions and prospects for further studies

In this article, we have reviewed advances in the reconstruction of climate and extreme events in China over the last 2000 years with emphasis on high-resolution proxies, paleoclimatic reconstructions, and results on the general characteristics of climate changes from decadal to centennial scales. The main conclusions can be summarized as follows:

(1) Over the last 10 years, many new climate reconstructions have been reported for China, including annual and decadal resolution series for temperature and precipitation for eastern China derived from historical documents. In western China, reconstructions were derived from tree-ring and other natural archives. The new reconstructions that are available provide more proxies and better spatial coverage to allow us to understand the characteristics of climate change in China as well as uncertainties at regional scales. We are now able to reconstruct high-resolution temperature series and spatial patterns of precipitation for the whole of China over past millennia by synthesizing available multi-proxies.

(2) An updated 2000-year-long temperature reconstruction for the whole of China, derived by synthesizing high confidence regional temperature signals from 28 proxies, shows that warm intervals occurred in the periods AD 1–200, AD 551–760, AD 951–1320, and after 1921, while cold intervals were in AD 201–350, AD 441–530, AD 781–950, and 1321–1920. Moreover, the rate of temperature change over the last 2000 years shows that, on a 100-year timescale, the warming rate for the whole of China in the 20th century was

only 0.6°C/100 a, while the peak warming rate for the period from the LIA to the 20th century reached 1.1°C/100 a, which was the greatest rate of change in the last 500 years and probably the last 2000 years.

(3) In the eastern monsoonal region of China, significant cycles of variation in precipitation were 90–100a, 70–80a, 43–48a, 35a, 25–27a, and 17–18a on the North China Plain; 90–100a, 73–75a, 63–68a, 55a, 45a, 37a, and 26a in the Jiang-Huai area; and 85–100a, 75–77a, 58–65a, 37–39a, 31a and 26a in the Jiang-Nan area. While the spatial pattern of drought-to-flood for the ensemble mean of all cold periods showed an east-to-west distribution pattern, for all warm periods there was a tri-pole pattern with drought to the south of 25°N, floods in the region 25°–30°N, and droughts north of 30°N. While the arid and semi-arid zones of northwest China were relatively dry in the period between AD 1000 and 1350, they were wet between AD 1500 and 1850, and tended to be moist in recent decades. In the area between the northeastern Qinghai-Tibet Plateau and the western margins of the Qinling Mountains (i.e., the linking area between the monsoonal climate in the east, the continental arid climate in the northwest, and the highland cold climate on the Qinghai-Tibet Plateau), there was evidence for centennial-scale oscillations in precipitation over the last 1000 years, interrupted by several multi-decadal severe drought events, in particular two extreme examples in the 1480s and 1710s.

(4) Extremely cold winters that occurred in China within the period 1500–1900 were more frequent than that after 1950. Indeed, intensity of regional heat waves experienced recently in the context of global warming may not exceed natural climatic variability seen during historical times. In eastern China, extreme drought events were more frequent in the periods between 301–400, 751–800, 1051–1150, 1501–1550, and 1601–1650, while extreme flooding events were more frequent in the periods between 101–150, 251–300, 951–1000, 1701–1750, 1801–1850, and 1901–1950. Between 1551 and 1600, extreme drought and flood events occurred together most frequently. Examples of exceptional droughts, such as those that occurred in eastern China within the periods 1586–1589, 1638–1641, 1876–1878, and 1965–1966, may be triggered by large volcanic eruptions and amplified both by volcanic activities and El Niño events.

(5) Years of extreme drought, reconstructed from tree rings and other proxies at most sites or small areas in western China, thought to occur frequently before 1900, may in fact be comparable to the most extreme example recorded by instrument data since 1950. Although extreme drought events seem to be more frequent since 2006, events that were just as severe as occurred in the early 21st century, may not have been passed those droughts recorded before 1900.

The achievements reviewed in this paper also provide a number of opportunities and challenges for further study in this field. In particular, more works are needed on the following issues:

(1) To understand the level of accuracy for proxy presenting climate, to reconstruct climate at accurate temporal and spatial resolutions, and to quantify the nature of uncertainties in these reconstructions. This is an issue because most proxies are correlated not only to temperature and precipitation but also to the co-linear of many other climatic parameters. Different proxies may capture variability well at different temporal and spatial scales and in different seasons.

(2) To develop strategies for compiling published (or soon to be published) proxy records of sub-annual to multi-decadal-resolution and their associated metadata derived from different paleoclimate archives. To develop better statistical approaches and skills for the synthesis and assimilation of multi-proxies for spatially gridded explicit reconstructions of homogeneous long-term temperature and precipitation. The aims are to understand changes in spatial patterns from inter-annual to centennial scales and to provide comparable datasets for paleoclimate models.

(3) To achieve a better understanding of past regional climatic and environmental dynamics through comparisons of reconstructions and model simulations, with a focus on the modes of climate variability in the past at inter-annual to centennial scales and teleconnections, and rapid and extreme climate events at the regional scale as well as the linkages between regional- and global-scale changes (e.g., global-scale abrupt and gradual Earth System changes and their underlying processes), their response to changes in forcings, internal feedbacks and teleconnections.

(4) To address long-term interactions between past climatic conditions, ecological processes and human activities over the last 2000 years via comparisons of regional-scale reconstructions of environmental and climatic processes and evidence of past human activities obtained from historical, paleoecological and archaeological records. These data will enable an improved understanding of the impacts of extreme events, abrupt and gradual changes on human activities, the roles of different natural and anthropogenic drivers in forcing environmental change, the feedbacks between human activity and the natural system, as well as the skills, ways and strategies for humans to adapt to extreme events, abrupt and gradual changes in past regional climate and the earth system.

References

Bi Yingfeng, Xu Jianchu, Gebrekirstos A *et al.*, 2015. Assessing drought variability since 1650 AD from tree-rings on the Jade Dragon Snow Mountain, southwest China. *International Journal of Climatology*, 35(14): 4057–4065.

Bird BW, Polisar PJ, Lei Yanbin *et al.*, 2014. A Tibetan lake sediment record of Holocene Indian summer monsoon variability. *Earth and Planetary Science Letters*, 399: 92–102

Bradley RS, Sheu D, Wang WC, 1993. High-resolution paleoclimate records from monsoon Asia. *Eos*, *Transactions-American Geophysical Union*, 74(51): 601–604.

CAMS (Chinese Academy of Meteorological Sciences), 1981. China Meteorological Administration. Yearly Charts of Dryness/Wetness in China for the Last 500-year Period. Beijing: SinoMaps Press. (in Chinese)

Chen Fahu, Chen Jianhui, Holmes J *et al.*, 2010. Moisture changes over the last millennium in arid Central Asia: A review, synthesis and comparison with monsoon region. *Quaternary Science Reviews*, 29(7): 1055–1068.

Christiansen B, Ljungqvist F C, 2011. Reconstruction of the extratropical NH mean temperature over the last millennium with a method that preserves low-frequency variability. *Journal of Climate*, 24(23): 6013–6034.

Christiansen B, Ljungqvist F C, 2012. The extra-tropical Northern Hemisphere temperature in the last two millennia: Reconstructions of low-frequency variability. *Climate of the Past*, 8(2): 765–786.

Chu Guoqiang, Sun Qing, Wang Xiaohua *et al.*, 2011. Seasonal temperature variability during the past 1600 years recorded in historical documents and varved lake sediment profiles from northeastern China. *The Holocene*, 22(7): 785–792.

Chu Ko-Chen, 1973. A preliminary study on the climatic fluctuations during the last 5000 years in China. *Scientia Sinica*, 16(2): 226–256.

Cook E R, Anchukaitis K J, Buckley B M *et al*., 2010. Asian monsoon failure and megadrought during the last millennium. *Science*, 328(5977): 486–489.

Cosford J, Qing Hairuo, Eglington B *et al*., 2008. East Asian monsoon variability since the mid-Holocene recorded in a high-resolution, absolute-dated aragonite speleothem from eastern China. *Earth and Planetary Science Letters*, 275(3): 296–307.

Cui Yingfang, Wang Yongjin, Cheng Hai *et al*., 2012. Isotopic and lithologic variations of one precisely-dated stalagmite across the Medieval/LIA period from Heilong Cave, central China. *Climate of the past*, 8(5): 1541–1550.

Ding Lingling, Ge Quansheng, Zheng Jingyun *et al*., 2014. Variations in the starting date of the pre-summer rainy season in South China, 1736–2010. *Journal of Geographical Sciences*, 24(5): 845–857.

Ding Lingling, Ge Quansheng, Zheng Jingyun *et al*., 2015. Variations in annual winter mean temperature in South China since 1736. *Boreas*. doi: 10.1111/bor.12144.

EC-SCNARCC, 2011. The Second National Assessment Report on Climate Change. Beijing: Science Press. (in Chinese)

Fan Zexin, Brauning A, Cao Kunfang, 2008. Tree-ring based drought reconstruction in the central Hengduan Mountains region (China) since AD 1655. *International Journal of Climatology*, 28(14): 1879–1887.

Fang Keyan, Gou Xiaohua, Chen Fahu *et al*., 2010. Reconstructed droughts for the southeastern Tibetan Plateau over the past 568 years and its linkages to the Pacific and Atlantic Ocean climate variability. *Climate Dynamics*, 35(4): 577–585.

Ge Quansheng, Guo Xifeng, Zheng Jingyun *et al*., 2008b. Meiyu in the middle and lower reaches of the Yangtze River since 1736. *Chinese Science Bulletin*, 53(1): 107–114.

Ge Quansheng, Hao Zhixin, Tian Yanyu *et al*., 2011b. The rainy season in the northwestern part of the East Asian summer monsoon in the 18th and 19th centuries. *Quaternary International*, 229(1): 16–23.

Ge Quansheng, Hao Zhixin, Zheng Jingyun *et al*., 2013. Temperature changes over the past 2000 yr in China and comparison with the Northern Hemisphere. *Climate of the Past*, 9(3): 1153–1160.

Ge Quansheng, Liu Haolong, Zheng Jingyun *et al*., 2010a. Reconstructing temperature change in Central East China during 601–920 AD. *Chinese Science Bulletin*, 55(34): 3944–3949.

Ge Quansheng, Zhang Xuezhen, Hao Zhixin *et al*., 2011a. Rates of temperature change in China during the past 2000 years. *Science China Earth Sciences*, 54(11): 1627–1634.

Ge Quansheng, Zheng Jingyun, Fang Xiuqi *et al*., 2003. Winter half-year temperature reconstruction for the middle and lower reaches of the Yellow River and Yangtze River, China, during the past 2000 years. *The Holocene*, 13(6): 933–940.

Ge Quansheng, Zheng Jingyun, Hao Zhixin *et al*., 2005. Reconstruction of historical climate in China: High-resolution precipitation data from Qing Dynasty Archives. *Bulletin of the American Meteorological Society*, 86(5): 671–679.

Ge Quansheng, Zheng Jingyun, Hao Zhixin *et al*., 2010b. Temperature variation through 2000 years in China: An uncertainty analysis of reconstruction and regional difference. *Geophysical Research Letters*, 37(3): L03703.

Ge Quansheng, Zheng Jingyun, Hao Zhixin *et al*., 2014. State-of-the-arts in the study of climate changes over China for the past 2000 years. *Acta Geographica Sinica*, 69(9): 1248–1258. (in Chinese)

Ge Quansheng, Zheng Jingyun, Tian Yanyu *et al*., 2008a. Coherence of climatic reconstruction from historical documents in China by different studies. *International Journal of Climatology*, 28(8): 1007–1024.

Gong Gaofa, Zhang Piyuan, Wu Xiangding *et al*., 1983. The Research Methods of Climate Changes during Historical Times. Beijing: Science Press. (in Chinese)

Gou Xiaohua, Deng Yang, Gao Linlin *et al*., 2015a. Millennium tree-ring reconstruction of drought variability in the eastern Qilian Mountains, Northwest China. *Climate Dynamics*, 45(7): 1761–1770.

Gou Xiaohua, Gao Linlin, Deng Yang *et al*., 2015b. An 850-year tree-ring-based reconstruction of drought history in the western Qilian Mountains of northwestern China. *International Journal of Climatology*, 35(11): 3308–3319.

Hao Zhixin, Ge Quansheng, Zheng Jingyun *et al*., 2007. 2006 extreme drought event of Chongqing. *Geographical*

Research, 26(4): 828–834. (in Chinese)

Hao Zhixin, Zheng Jingyun, Ge Qaunsheng *et al*., 2011. Historical analogues of the 2008 extreme snow event over Central and Southern China. *Climate Research*, 50(2): 161–170.

Hao Zhixin, Zheng Jingyun, Ge Quansheng *et al*., 2012. Winter temperature variations over the middle and lower reaches of the Yangtze River since 1736 AD. *Climate of the Past*, 8(3): 1023–1030.

Hao Zhixin, Zheng Jingyun, Ge Quansheng, 2008. Precipitation cycles in the middle and lower reaches of the Yellow River (1736–2000). *Journal of Geographical Sciences*, 18(1): 17–25.

Hao Zhixin, Zheng Jingyun, Ge Quansheng, 2009. Variations in the summer monsoon rainbands across eastern China over the past 300 years. *Advances in Atmospheric Sciences*, 26(4): 614–620.

Hao Zhixin, Zheng Jingyun, Ge Quansheng. 2010a. Variations of extreme drought/flood events over eastern China during the past 2000 years. *Climatic and Environmental Research*, 15(4): 388–394. (in Chinese)

Hao Zhixin, Zheng Jingyun, Wu Guofeng *et al*., 2010b. 1876–1878 severe drought in North China: Facts, impacts and climatic background. *Chinese Science Bulletin*, 55(26): 3001–3007.

Hao Zhixin, Zheng Jingyun, Zhang Xuezhen *et al*., 2016. Spatial patterns of precipitation anomalies in eastern China during centennial cold and warm periods of the past 2000 years. *International Journal of Climatology*, 36(1): 467–475.

He Yaoqi, Wang Yongjin, Kong Xinggong *et al*., 2005. High resolution stalagmite $\delta^{18}O$ records over the past 1000 years from Dongge Cave in Guizhou. *Chinese Science Bulletin*, 50(10): 1003–1008.

Hegerl G C, Crowley T J, Allen M *et al*., 2007. Detection of human influence on a new, validated 1500-year temperature reconstruction. *Journal of Climate*, 20(4): 650–666.

Hu Chaoyong, Henderson G M, Huang Junhua *et al*., 2008. Quantification of Holocene Asian monsoon rainfall from spatially separated cave records. *Earth and Planetary Science Letters*, 266(3): 221–232.

IPCC, 2001. Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, USA: Cambridge University Press.

IPCC, 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, USA: Cambridge University Press.

Jones P D, Briffa K R, Osborn T J *et al*., 2009. High-resolution palaeoclimatology of the last millennium: A review of current status and future prospects. *The Holocene*, 19(1): 3–49.

Jones P D, Mann M E, 2004. Climate over past millennia. *Reviews of Geophysics*, 42(2): RG2002.

Li Jinbao, Gou Xiaohua, Cook E R *et al*., 2006. Tree-ring based drought reconstruction for the central Tien Shan area in Northwest China. *Geophysical Research Letters*, 33(7): L07715.

Li Zongshan, Shi Chunming, Liu Yongbo *et al*., 2011. Winter drought variations based on tree-ring data in Gaoligong Mountain, northwestern Yunnan, China, AD 1795–2004. *Pakistan Journal of Botany*, 43(5): 2469–2478.

Liu Jianbao, Chen FaHu, Chen Jianhui *et al*., 2011. Humid Medieval Warm Period recorded by magnetic characteristics of sediments from Gonghai Lake, Shanxi, North China. *Chinese Science Bulletin*, 56(23): 2464–2474.

Liu Xiaohong, Qin Dahe, Shao Xuemei *et al.,* 2005. Temperature variations recovered from tree-rings in the middle Qilian Mountain over the last millennium. *Science in China Series D Earth Sciences*, 48(4): 521–529.

Liu Xiaohong, Shao Xuemei, Zhao Liangju *et al*., 2007. Dendroclimatic temperature record derived from tree ring width and stable carbon isotope chronologies in the middle Qilian Mountains, China. *Arctic*, *Antarctic*, *and Alpine Research*, 39, 651–657.

Liu Xingqi, Yu Zhitong, Dong Hailiang *et al*., 2014. A less or more dusty future in the northern Qinghai-Tibetan Plateau? *Scientific Reports*, 2014, 4: No. 6672. doi: 10.1038/srep06672.

Liu Yu, An Zhisheng, Linderholm HW *et al.,* 2009. Annual temperatures during the last 2485 years in the mid-eastern Tibetan Plateau inferred from tree rings. *Science in China Series D*: *Earth Sciences*, 52(3): 348–359.

Liu Yu, An Zhisheng, Ma Haizhou *et al*., 2006. Precipitation variation in the northeastern Tibetan Plateau recorded by the tree rings since 850 AD and its relevance to the Northern Hemisphere temperature. *Science in*

China Series D Earth Sciences, 49(4): 408–420.

Liu Yu, Sun Bo, Song Huiming *et al*., 2013. Tree-ring-based precipitation reconstruction for Mt. Xinglong, China, since AD 1679. *Quaternary International*, 283: 46–54.

Liu Zhonghui, Henderson ACG, Huang Yongsong, 2006. Alkenone-based reconstruction of late-Holocene surface temperature and salinity changes in Lake Qinghai, China. *Geophysical Research Letters*, 33(9): L09707.

Ljungqvist F C, 2010. A new reconstruction of temperature variability in the extra-tropical Northern Hemisphere during the last two millennia. *Geografiska Annaler: Series A, Physical Geography*, 92(3): 339–351.

Lu Daren, Ding Zhongli, 2012. Climate Change: Carbon Budget and Relevant Issues. *Bulletin of Chinese Academy of Sciences*, 27(3): 395–402. (in Chinese)

Mann M E, Jones P D, 2003. Global surface temperatures over the past two millennia. *Geophysical Research Letters*, 30(15): ID 1820.

Mann M E, Zhang Z H, Hughes M K *et al*., 2008. Proxy-based reconstructions of hemispheric and global surface temperature variations over the past two millennia. *Proceedings of the National Academy of Sciences*, 105(36): 13252–13257.

Mann M E, Zhang Z H, Rutherford S *et al*., 2009. Global signatures and dynamical origins of the Little Ice Age and Medieval Climate Anomaly. *Science*, 326(5957): 1256–1260.

Moberg A, Sonechkin D M, Holmgren K *et al*., 2005. Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data. *Nature*, 433(7026): 779–787.

National Research Council, 2006. Surface Temperature Reconstructions for the Last 2000 Years. Washington DC: The National Academies Press.

Osborn T J, Briffa K R, 2006. The spatial extent of 20th-century warmth in the context of the past 1200 years. *Science*, 311(5762): 841–844.

PAGES 2k Consortium, 2013. Continental-scale temperature variability during the past two millennia. *Nature Geoscience*, 6: 339–346.

PAGES, 2009. Science Plan and Implementation Strategy. IGBP Report No.57. Stockholm: IGBP Secretariat.

Qin Dahe, 2015. China National Assessment Report on Risk Management and Adaptation of Climate Extremes and Disasters. Beijing: Science Press. (in Chinese)

Qin Dahe, Chen Panqin, Ge Quansheng, 1998. Advances in Global Change Studies of China. Beijing: China Ocean Press.

Shao Xuemei, Huang Lei, Liu Hongbin *et al*., 2005. Reconstruction of precipitation variation from tree rings in recent 1000 years in Delingha, Qinghai. *Science in China Ser. D Earth Sciences*, 48(7): 939–949.

Shao Xuemei, Liang Eryuan, Huang Lei *et al*., 2006. A reconstructed precipitation series over the past millennium in the northeastern Qaidam Basin. *Advances in Climate Change Research*, 2(3): 122–126. (in Chinese)

Shao Xuemei, Xu Yan, Yin Zhiyong *et al*., 2010. Climatic implications of a 3585-year tree-ring width chronology from the northeastern Qinghai-Tibetan Plateau. *Quaternary Science Reviews*, 29(17): 2111-2122.

Shen Caiming, Wang Wei-Chyung, Hao Zhixin *et al*., 2007. Exceptional drought events over eastern China during the last five centuries. *Climatic Change*, 85(3/4): 453–471.

Shen Caiming, Wang Wei-Chyung, Peng Youbing *et al*., 2009. Variability of summer precipitation over eastern China during the last millennium. *Climate of the Past*, 5(2): 129–141.

Shi Feng, Yang Bao, Von Gunten L, 2012. Preliminary multiproxy surface air temperature field reconstruction for China over the past millennium. *Science China Earth Sciences*, 55(12): 2058–2067.

Shi Xinghe, Qin Ningsheng, Shao Xuemei *et al*., 2009. Precipitation change over the past 1000 years recorded in Sabina Tibetica Tree Rings in Lake Qinghai Basin. *Journal of Lake Sciences*, 21(4): 579–586. (in Chinese)

Tan Liangcheng, Cai Yanjun, An Zhisheng *et al*., 2011. Centennial- to decadal-scale monsoon precipitation variability in the semi-humid region, northern China during the last 1860 years: Records from stalagmites in Huangye Cave. *The Holocene*, 21(2): 287–296.

Tan Liangcheng, Cai Yanjun, Cheng Hai *et al*., 2009. Summer monsoon precipitation variations in central China over the past 750 years derived from a high-resolution absolute-dated stalagmite. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 280(3): 432–439.

Wang Jianglin, Yang Bao, Ljungqvist F C, 2015. A millennial summer temperature reconstruction for the eastern Tibetan Plateau from tree ring width. *Journal of Climate*, 28(13): 5289–5304.

Wang Jianglin, Yang Bao, Qin Chun *et al*., 2014. Tree-ring inferred annual mean temperature variations on the southeastern Tibetan Plateau during the last millennium and their relationships with the Atlantic multidecadal oscillation. *Climate Dynamics*, 43(3): 627–640.

Wang Pinxian, Chai Yucheng, Guo Zhengtang *et al*., 2005. Chinese paleoscience. *PAGES News*, 13(2): 2–23.

Wang P K, Zhang De'er, 1992. Recent studies of the reconstruction of East Asian monsoon climate in the past using historical documents of China. *Journal of the Meteorological Society of Japan*, 70(1B): 423–446.

Wang Shaowu, Gong Daoyi, Zhu Jinhong, 2001. Twentieth-century climatic warming in China in the context of the Holocene. *The Holocene*, 11(3): 313–321.

Wang Shaowu, Wen Xinyu, Luo Yong *et al*., 2007. Reconstruction of temperature series of China for the last 1000 years. *Chinese Science Bulletin*, 52(23): 3272–3280.

Wang Wei-Chyung, Ge Quansheng, Hao Zhixin *et al*., 2008. Rainy season at Beijing and Shanghai since 1736. *Journal of the Meteorological Society of Japan*, 86(5): 827–834.

Wang Wenzhi, Liu Xiaohong, Xu Guobao *et al*., 2013. Moisture variations over the past millennium characterized by Qaidam Basin tree-ring δ^{18}O. *Chinese Science Bulletin*, 58(32): 3956–3961.

Yan Junhui, Ge Quansheng, Liu Haolong *et al*., 2014. Reconstruction of sub-decadal winter half-year temperature during 1651–2010 for the North China Plain using records of frost date. *Atmospheric and Climate Sciences*, 4(2): 211–218.

Yang Bao, Braeuning A, Johnson K R *et al*., 2002. General characteristics of temperature variation in China during the last two millennia. *Geophysical Research Letters*, 29(9): 38-1–38-4.

Yang Bao, Kang Shuyuan, Ljungqvist F C *et al*., 2014b. Drought variability at the northern fringe of the Asian summer monsoon region over the past millennia. *Climate Dynamics*, 43(3): 845–859.

Yang Bao, Qin Chun, Wang Jianglin *et al*., 2014a. A 3,500-year tree-ring record of annual precipitation on the northeastern Tibetan Plateau. *Proceedings of the National Academy of Sciences*, 111(8): 2903–2908.

Yang Fengmei, Shi Feng, Kang Shuyuan *et al*., 2013. Comparison of the dryness/wetness index in China with the Monsoon Asia Drought Atlas. *Theoretical and Applied Climatology*, 114(3/4): 553–566.

Ye Duzheng, Chen Panqin, 1993. First Report of IGBP-related Studies in China. Beijing: China Meteorological Press.

Ye Duzheng, Lin Hai, 1995. China Contribution to Global Change Studies. Beijing: Science Press.

Zhang De'er, 2004. A Compendium of Chinese Meteorological Records of the Last 3,000 Years. Nanjing: Jiangsu Education Press, 1–3666.

Zhang De'er, Gaston D, 2004. Northern China maximum temperature in the summer of 1743: A historical event of burning summer in a relatively warm climate background. *Chinese Science Bulletin*, 49(23): 2508–2514.

Zhang De'er, Li Xiaoquan, Liang Youye, 2003. Supplement of yearly charts of dryness/wetness in China for the last 500-year period, 1993–2000. *Journal of Applied Meteorological Science*, 14(3): 379–389. (in Chinese)

Zhang Jiacheng, 1988. The Reconstruction of Climate in China for Historical Times. Beijing: Science Press.

Zhang Jiacheng, Crowley T J, 1989. Historical climate records in China and reconstruction of past climates. *Journal of Climate*, 2(8): 833–849.

Zhang Piyuan, 1996. Climate Change in China during Historical Times. Jinan: Shandong Science and Technology Press. (in Chinese)

Zhang Piyuan, Ge Qaunsheng, Wang Zheng, 1997. Past climate in China, derived from ancient writings. In: Space Science in China. Amsterdam: Gordon and Breach Science Publisher.

Zhang Piyuan, Ge Quansheng, Zheng Jingyun, 1999. Research Activities in Task 2 (Proxy Data) at IG/CAS. In: Greenhouse Effect and Climate Change. Beijing: China Ocean Press.

Zhang Piyuan, Gong Gaofa, 1980. Ancient precipitation records in China. *World Meteorological Organization Bulletin*, 29: 7–11.

Zhang Pingzhong, Cheng Hai, Edwards R L *et al*., 2008. A test of climate, sun, and culture relationships from an 1810-year Chinese cave record. *Science*, 322(5903): 940–942.

Zhang Qibin, Cheng Guodong, Yao Tandong *et al*., 2003. A 2,326-year tree-ring record of climate variability on the northeastern Qinghai-Tibetan Plateau. *Geophysical Research Letters*, 30(14): 1739.

Zhang Yong, Shao Xuemei, Yin Zhiyong *et al*., 2011b. Characteristics of extreme droughts inferred from tree-ring data in the Qilian Mountains, 1700–2005. *Climate Research*, 50(2): 141–159.

Zhang Yong, Shao Xuemei, Yin Zhiyong *et al.,* 2014. Millennial minimum temperature variations in the Qilian Mountains, China: Evidence from Tree rings. *Climate of the Past*, 10(5): 1763–1778.

Zhang Yong, Tian Qinhua, Gou Xiaohua *et al*., 2011a. Annual precipitation reconstruction since AD 775 based on tree rings from the Qilian Mountains, northwestern China. *International Journal of Climatology*, 31(3): 371–381.

Zhao Kan, Wang Yongjin, Edwards R L *et al*., 2015. A high-resolved record of the Asian summer monsoon from Dongge Cave, China for the past 1200 years. *Quaternary Science Reviews*, 122: 250–257.

Zheng Jingyun, Ding Lingling, Hao Zhixin *et al*., 2012. Extreme cold winter events in southern China during AD 1650–2000. *Boreas*, 41(1): 1–12.

Zheng Jingyun, Ge Quansheng, Hao Zhixin *et al*., 2014a. Paleoclimatology proxy recorded in historical documents and method for reconstruction on climate change. *Quaternary Sciences*, 34(6): 1186–1196. (in Chinese)

Zheng Jingyun, Hao Zhixin, Fang Xiuqi *et al*., 2014c. Changing characteristics of extreme climate events during past 2000 years in China. *Progress in Geography*, 33(1): 3–12. (in Chinese)

Zheng Jingyun, Hao Zhixin, Ge Quansheng, 2005b. Variation of precipitation for the last 300 years over the middle and lower reaches of the Yellow River. *Science in China Series D: Earth Sciences*, 48(12): 2182–2193.

Zheng Jingyun, Hao Zhixin, Zhang Xuezhen *et al*., 2014b. Drought/flood spatial patterns in centennial cold and warm periods of the past 2000 years over eastern China. *Chinese Science Bulletin*, 59(30): 2964–2971. (in Chinese)

Zheng Jingyun, Man Zhimin, Fang Xiuqi *et al*., 2005a. Temperature variation in the eastern China during Wei, Jin and South-North Dynasties (220–580AD). *Quaternary Sciences*, 25(2): 129–140. (in Chinese)

Zheng Jingyun, Wang Wei-Chyung, Ge Quansheng *et al*., 2006. Precipitation variability and extreme events in eastern China during the past 1500 years. *Terrestrial Atmospheric and Oceanic Sciences*, 17(3): 579–592.

Zhu Haifeng, Fang Xiuqi, Shao Xuemei *et al*., 2009. Tree ring-based February–April temperature reconstruction for Changbai Mountain in Northeast China and its implication for East Asian winter monsoon. *Climate of the Past*, 5(4): 661–666.

Zhu Haifeng, Zheng Yonghong, Shao Xuemei *et al*., 2008. Millennial temperature reconstruction based on tree-ring widths of Qilian juniper from Wulan, Qinghai Province, China. *Chinese Science Bulletin*, 53(24): 3914–3920.

Supplement Table 1 Recent studies on temperature reconstruction more than 300 years derived from tree-ring

Sampling site	Lon (°E)	Lat (°N)	Period	Reconstructed	Proxy type	Source
Gaoligong Mountains	98.4-98.5	27.8	1690-2008	August-September mean temperature	Maximum latewood density	Li *et al.* (2015)
Eastern Tibetan Plateau	85-105	25-40	1000-2005	June-August mean temperature	Tree ring width	Wang *et al.* (2015)
Qamdo region	96.97	31.08	1594-2006	October-January minimum temperature	Tree ring width	Zhang *et al.* (2015)
Central Qilian Mountains	99.7	38.7	670-2012	January-August minimum temperature	Tree ring width	Zhang *et al.* (2014)
Bangda and Zuogong	97.4-97.9	30.0-30.1	1563-2011	April-September mean temperature	Maximum latewood density	Duan & Zhang(2014)
Baiyu	99.8	31.1	1446-2008	June-July mean temperature	Tree ring width	Deng *et al.* (2014)
Qamdo region	97.0	31.0	984-2009	annual mean temperature	Tree ring width	Wang *et al.* (2014)
Qumalai and Zhiduo	96.2-96.3	33.7-33.8	1395-2010	annual minimum temperature	Tree ring width	He *et al.* (2014)
Shimen Mountain	106.2	34.5	1630-2011	May-July mean temperature	Tree ring width	Song *et al.* (2014)
Kaiduhe River watershed	84.9-85.1	42.4	1680-2011	September-March mean temperature	Tree ring width	Zhang *et al.* (2013)
Geza	99.8	28.4	1475-2003	June-August mean temperature	Tree ring width	Li *et al.* (2012)
East Altay	87.6-90.9	46.7-48.4	1613-2006	June-July mean temperature	Tree ring width	Hu *et al.* (2012)
Leiwuqi	96.5	31.3	1440-2006	May-June mean temperature	Tree ring width	Zhu *et al.* (2011a)
Bomi and Linzhi	96.5-96.8	29.5-29.6	1385-2002	August mean temperature	Tree ring width	Zhu *et al.* (2011b)
Zaduo area	95.7	32.7	1360-2005	May-June maximum temperature	Tree ring width	Shi *et al.* (2010)
Gaoligong Mountains	98.4	27.8	1411-2005	May-August temperature	Tree ring width	Fan *et al.* (2010)
Eastern Tibetan Plateau	97.0-98.5	29.7-31.1	1695-2000	August-September mean temperature	Maximum latewood density	Wang *et al.* (2010)
Angren county	87.2	29.3	1612-1998	annual mean temperature	Tree ring width	Yang *et al.* (2010a)
Bajie town of Linzhi county	94.3	29.4	1377-1998	mean January-June temperature	Tree ring width	Yang *et al.* (2010b)
Altay	87.8-87.9	48.3	1570-2005	June mean temperature	Tree ring width	Shang *et al.* (2010)
Sunan county	98.8	39.0	1700-2000	May-June mean temperature	Tree ring width	Tian *et al.* (2009)
northeastern Tibetan Plateau	98-99	35.5-37	BC484-2000	annual mean temperature	Tree ring width	Liu *et al.* (2009)
Hutubi River Basin	86.4-86.6	43.5-43.7	1690-2002	May-June maximum temperature	Tree ring width	Chen *et al.* (2009)
Qiemuqu	99.7-99.8	34.7-34.8	1300-2000	April-September maximum temperature	Tree ring width	Gou *et al.* (2008)
Wulan County	98.7	37.0	1000-2002	September-April mean temperature	Tree ring width	Zhu *et al.* (2008)
Yushu region	96.5-97.7	31.8-32.6	1624-2002	June-August minimum temperature	Tree ring width	Liang *et al.* (2008)
Yili Prefecture	80.2-85.0	42.2-44.8	1682-1980	June to August maximum temperature	Tree ring width	Fan *et al.* (2008)
Xiqing Mountains	100.8	34.8	1577-2002	October-April minimum temperature	Tree ring width	Gou *et al.* (2007)
Jinghe	82.9-83.2	44.1-44.2	1468-2001	May-August mean temperature	Tree ring width	Yu *et al.* (2007)
Boertala River Basin	80.8-82.1	44.3-44.9	1540-2000	July-August mean temperature	Tree ring width	Pan *et al.* (2007)
Sidalong	99.1	38.5	1000-2000	December-April mean temperature	Tree ring width	Liu *et al.* (2005)

Chen Feng, Yuan Yujiang, Wei Wenshou *et al.*, 2009. Spring mean maximum temperature series and its variation properties in Hutubi River Basin during the last 313 years. *Journal of Desert Research*, 29(1): 162–166. (in Chinese)

Deng Yang, Gou Xiaohua, Gao Linlin *et al.*, 2014. Early-summer temperature variations over the past 563 yr inferred from tree rings in the Shaluli Mountains, southeastern Tibet Plateau. *Quaternary Research*, 81(3): 513–519.

Duan Jianping, Zhang Qibin, 2014. A 449-year warm-season temperature reconstruction in the southeastern Tibetan Plateau and its relation to solar activity. *Journal of Geophysical Research Atmospheres*, 119(20): 11578–11592.

Fan Minjie, Yuan Yujiang, Wei Wenshou *et al.*, 2008. Interpolation and Analysis of Mean Summer Maximum Temperature in Yili Prefecture in the West Tianshan Mountains, *China. Arid Z one Research*, 25(1): 75–81. (in Chinese)

Fan Zexin, Brauning A, Tian Qinhua *et al.*, 2010. Tree ring recorded May-August temperature variations since AD 1585 in the Gaoligong Mountains, southeastern Tibetan Plateau. *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*, 296(1): 94–102.

Gou Xiaohua, Chen Fahu, Jacoby G *et al.*, 2007. Rapid tree growth with respect to the last 400 years in response to climate warming, northeastern Tibetan Plateau. *International Journal of Climatology*, 27(11): 1497–1503.

Gou Xiaohua, Chen Fahu, Yang Meixue *et al.*, 2008. Asymmetric variability between maximum and minimum temperatures in northeastern Tibetan Plateau: evidence from tree rings. *Science in China Series D*: *Earth Sciences*, 51(1): 41–55.

He Minhui, Yang Bao, Datsenko N M, 2014. A six hundred-year annual minimum temperature history for the central Tibetan Plateau derived from tree-ring width series. *Climate Dynamics*, 43(3): 641–655.

Hu Yicheng, Yuan Yujiang, Wei Wenshou *et al.*, 2012. Tree-ring reconstruction of mean June-July temperature during 1613–2006 in East Altay, Xinjiang of China. *Journal of Desert Research*, 32(4): 1003–1009. (in Chinese)

Li Mingyong, Wang Lili, Fan Zexin *et al.*, 2015. Tree-ring density inferred late summer temperature variability over the past three centuries in the Gaoligong Mountains, southeastern Tibetan Plateau. *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*, 422: 57–64.

Li Zongshan, Zhang Qibin, Ma Keping, 2012. Tree-ring reconstruction of summer temperature for A.D. 1475–2003 in the central Hengduan Mountains, northwestern Yunnan, China. *Climatic Change*, 110(1/2): 455–467.

Liang Eeyuan, Shao Xuemei, Qin Ningsheng, 2008. Tree-ring based summer temperature reconstruction for the source region of the Yangtze River on the Tibetan Plateau. *Global and Planetary Change*, 61(s3/4): 313–320.

Liu Xiaohong, Qin Dahe, Shao Xuemei *et al.*, 2005. Temperature variations recovered from tree-rings in the middle Qilian Mountain over the last millennium. *Science in China Series D Earth Sciences*, 48(4): 521–529.

Liu Yu, An Zhisheng, Linderholm HW *et al.*, 2009. Annual temperatures during the last 2485 years in the mid-eastern Tibetan Plateau inferred from tree rings. *Science in China Series D*: *Earth Sciences*, 52(3): 348–359.

Pan Yating, Yuan Yujiang, Yu Shulong, 2007. Reconstruction and analysis of summer temperature sequence for Boertala River basin over past 461 years. *Journal of Desert Research*, 27(1): 159–164. (in Chinese)

Shang Huaming, Wei Wenshou, Yuan Yujiang *et al.*, 2010. The mean June temperature history of 436a in Altay reconstructed from tree ring. *Journal of Arid Land Resources and Environment*, 24(8): 116–121. (in Chinese)

Shi Xinghe, Qin Ningsheng, Zhu Haifeng *et al.*, 2010. May-June mean maximum temperature change during 1360–2005 as reconstructed by tree rings of Sabina Tibetica in Zaduo, Qinghai Province. *Chinese Science Bulletin*, 55(26): 3023–3029.

Song Huiming, Liu Yu, Li Qiang *et al.*, 2014. Tree-ring based May-July temperature reconstruction since AD 1630 on the Western Loess Plateau, China. *Plos One*, 9(4): e93504.

Tian Qinhua, Gou Xiaohua, Zhang Yong *et al.*, 2009. May-June mean temperature reconstruction over the past 300 years based on tree rings in the Qilian mountains of the Northeastern Tibetan Plateau. *IAWA Journal*, 30(4): 421–434.

Wang Jianglin, Yang Bao, Ljungqvist F C, 2015. A millennial summer temperature reconstruction for the Eastern Tibetan Plateau from tree ring width. *Journal of Climate*, 28(13): 5289–5304.

Wang Jianglin, Yang Bao, Qin Chun *et al*., 2014. Tree-ring inferred annual mean temperature variations on the southeastern Tibetan Plateau during the last millennium and their relationships with the Atlantic Multidecadal Oscillation. *Climate Dynamics*, 43(3): 627–640.

Wang Lili, Duan Jianping, Chen Jin *et al*., 2010. Temperature reconstruction from tree-ring maximum density of Balfour spruce in eastern Tibet, China. *International Journal of Climatology*, 30(7): 972–979.

Yang Bao, Kang Xingcheng, Brauning A *et al*., 2010b. A 622-year regional temperature history of southeast Tibet derived from tree rings. *The Holocene*, 20(2): 181–190.

Yang Bao, Kang Xingcheng, Liu Jingjing *et al*., 2010a. Annual temperature history in Southwest Tibet during the last 400 years recorded by tree rings. *International Journal of Climatology*, 30(7): 962–971.

Yu Shulong, Yuan Yujiang, He Qing *et al*., 2007. Reconstruction of temperature series from A.D. 1468–2001 in the Jinghe, Xinjiang. *Journal of Glaciology and Geocryology*, 29(3): 374–379. (in Chinese)

Zhang Ruibo, Yuan Yujiang, Wei Wenshou *et al*., 2015. Dendroclimatic reconstruction of autumn-winter mean minimum temperature in the eastern Tibetan Plateau since 1600 AD. *Dendrochronologia*, 33: 1–7.

Zhang Tongwen, Yuan Yujiang, Liu Yu *et al*., 2013. A tree-ring based temperature reconstruction for the Kaiduhe River watershed, northwestern China, since AD 1680: Linkages to the North Atlantic Oscillation. *Quaternary International*, 311: 71–80.

Zhang Yong, Shao Xuemei, Yin Zhiyong *et al*., 2014. Millennial minimum temperature variations in the Qilian Mountains, China: evidence from Tree rings. *Climate of the Past*, 10(5): 1763–1778.

Zhu Haifeng, Shao Xuemei, Yin Zhiyong *et al*., 2011a. Early summer temperature reconstruction in the eastern Tibetan Plateau since ad 1440 using tree-ring width of Sabina tibetica. *Theoretical and Applied Climatology*, 106(1/2): 45–53.

Zhu Haifeng, Shao Xuemei, Yin Zhiyong *et al*., 2011b. August temperature variability in the southeastern Tibetan Plateau since AD 1385 inferred from tree rings. *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*, 305(1): 84–92.

Zhu Haifeng, Zheng Yonghong, Shao Xuemei *et al*., 2008. Millennial temperature reconstruction based on tree-ring widths of Qilian juniper from Wulan, Qinghai Province, China. *Chinese Science Bulletin*, 53(24): 3914–3920.

Supplement Table 2 Recent studies on precipitation reconstructions more than 300 years by tree-ring

Sampling site	Lon (°E)	Lat (°N)	Period	Reconstructed	Proxy type	Source
Hutubi River Basin	86.38–86.65	43.53–43.72	1457–2009	April-May PDSI	Tree ring width	Chen *et al.* (2015)
Eastern Qilian Mountains	101.24–101.26	37.95–37.97	1009–2010	June-July SPEI	Tree ring width	Gou *et al.* (2015a)
Western Qilian Mountains	98.80–98.88	39.62	1161–2010	May-July PDSI	Tree ring width	Gou *et al.* (2015b)
Eastern Tibetan Plateau	91.51–102.02	29.45–37.37	1442–2005	May-July PDSI	Tree ring width	Zhang et al. (2015)
Eastern Tian-shan Mountains	93.96	43.31	1700–2008	July-August PDSI	$\delta^{18}O$	Xu *et al.* (2014)
Namlin Region	88.88–89.61	29.25–30.10	1485–2010	July-June precipitation	Tree ring width	Liu (2014)
Northeastern Tibetan Plateau	97.15–99.97	35.45–38.70	BC1500–2011	July-June precipitation	Tree ring width	Yang *et al.* (2014a)
Hengduan Mountains	99.93	29.15	1509–2006	September-June precipitation	Tree ring width	Gou *et al.* (2013)
Qaidam Basin	97.53	37.27	991–2010	relative humidity during growing season	$\delta^{18}O$	Wang *et al.* (2013)
Changling Mountains	103.68	37.45	1691–2006	September-July precipitation	Earlywood width	Chen *et al.* (2012)
Xiaolong Mountain	106.13	34.45	1607–2009	April-July precipitation	Tree ring width	Fang *et al.* (2012a)
Kongtong Mountain	106.51	35.54	1615–2009	May-July PDSI	Tree ring width	Fang *et al.* (2012b)
Northern Xinjiang	84.78	44.02	1468–2004	July-June precipitation	Tree ring width	Yang *et al.* (2012)
Middle Qilian Mountain	99.73	38.78	1480–2000	August-July precipitation	Tree ring width	Tian *et al.* (2012)
Middle Tian-shan Mountains	84.63–88.21	43.53–44.06	1666–2003	August-July precipitation	Tree ring width	Gao *et al.* (2011)
Middle Qilian Mountains	99.67–99.70	38.68–38.71	775–2006	August-July precipitation	Tree ring width	Zhang *et al.* (2011)
Nilka County	83.60–83.69	43.64–43.67	1671–2006	last year's July-August precipitation	Tree ring width	Zhang *et al.* (2010)
Hengduan Mountains	99.29–99.45	27.31–27.59	1440–2007	May-April PDSI	Tree ring width	Fang *et al.* (2010a)
Guiqing Mountain	104.07–106.08	34.63–39.08	1618–2015	May-August PDSI	Tree ring width	Fang *et al.* (2010b)
Lake Qinghai Basin	98.4	37.31	942–2002	October-September precipitation	Tree ring width	Shi *et al.* (2009)
Hutubi River Basin	86.36–86.56	43.53–43.66	1690–2002	August-July precipitation	Tree ring width	Chen *et al.* (2009)
Aksu River Basin	79.09	41.55	1396–2005	August-April precipitation	Tree ring width	Zhang *et al.* (2009)
West Altay Prefecture	86.84	48.66	1481–2004	June-September precipitation	Tree ring width	Zhang *et al.* (2008)
Sogxian	94.29	31.63	1494–2004	May-June PDSI	Tree ring width	Wang *et al.* (2008)
Urumqi River Head	87.12–87.16	43.14–43.19	1535–2001	April-May precipitation	Tree ring width	Cui *et al.* (2007)
Ningwu Region	112.08	38.83	1686–2003	August-July precipitation	Tree ring width	Li *et al.* (2006)
Dulan	98.18	36.06	850–2002	July-June precipitation	Tree ring width	Liu *et al.* (2006)
Northeastern Qaidam Basin	97.06–98.66	36.68–37.51	566–2002	July-June precipitation	Tree ring width	Shao *et al.* (2006)
Kuitun River Basin	84.63–84.79	44.02–44.09	1624—2002	July–August precipitation	Tree ring width	Yu *et al.* (2005)
Qinghai Provinc	96.13–100.13	33.80–38.85	1479–1991	May-October precipitation	Tree ring width	Wang *et al.* (2005)
Delingha	97.23–98.42	36.68–37.47	1000–2001	July-June precipitation	Tree ring width	Shao *et al.* (2005)
Southern Qinghai Plateau	96.13–96.28	33.72–33.80	1550–2002	May-June moisture index	Tree ring width	Qin *et al.* (2003)
Dulan area	98	36.16	BC326–2000	May-June precipitation	Tree ring width	Zhang *et al.* (2003)

Chen Feng, Yuan Yujiang, Wei Wenshou *et al*., 2009. Reconstruction and analysis of precipitation in the Hutubi River Basin on the northern slope of the Tianshan Mountains during the last 313 years. *Arid Zone Research*, 26(1): 130–135. (in Chinese)

Chen Feng, Yuan Yujiang, Wei Wenshou *et al*., 2012. Tree-ring-based reconstruction of precipitation in the Changling Mountains, China, since AD 1691. *International Journal of Biometeorology*, 56(4): 765–774.

Chen Feng, Yuan Yujiang, Wei Wenshou *et al*., 2015. Tree-ring recorded hydroclimatic change in Tienshan mountains during the past 500 years. *Quaternary International*, 358: 35–41.

Cui Yu, Yuan Yujiang, Jin Hailong *et al*., 2007. Reconstruction and Analysis of 467-year Spring Precipitation Series in the Urumqi River Head. *Arid Land Geography*, 30(4): 496–500. (in Chinese)

Fang Keyan, Gou Xiaohua, Chen Fahu *et al*., 2010a. Reconstructed droughts for the southeastern Tibetan Plateau over the past 568 years and its linkages to the Pacific and Atlantic Ocean climate variability. *Climate Dynamics*, 35(4): 577–585.

Fang Keyan, Gou Xiaohua, Chen Fahu *et al*., 2010b. Tree-ring based drought reconstruction for the Guiqing Mountain (China): Linkages to the Indian and Pacific Oceans. *International Journal of Climatology*, 30(8): 1137–1145.

Fang Keyan, Gou Xiaohua, Chen Fahu *et al*., 2012a. Precipitation variability during the past 400 years in the Xiaolong Mountain (central China) inferred from tree rings. *Climate Dynamics*, 39(7/8): 1697–1707.

Fang Keyan, Gou Xiaohua, Chen Fahu *et al*., 2012b. Tree-ring based reconstruction of drought variability (1615–2009) in the Kongtong Mountain area, northern China. *Global and Planetary Change*, 80: 190–197.

Gao Weidong, Yuan Yujiang, Zhang Ruibo *et al*., 2011. The recent 338-year precipitation series reconstructed from tree-ring in northern slope of Tianshan Mountains. *Journal of Desert Research*, 31(6): 1535–1540. (in Chinese)

Gou Xiaohua, Deng Yang, Gao Linlin *et al*., 2015a. Millennium tree-ring reconstruction of drought variability in the eastern Qilian Mountains, Northwest China. *Climate Dynamics*, 45(7): 1761–1770.

Gou Xiaohua, Gao Linlin, Deng Yang *et al*., 2015b. An 850-year tree-ring-based reconstruction of drought history in the western Qilian Mountains of northwestern China. *International Journal of Climatology*, 35(11): 3308–3319.

Gou Xiaohua, Yang Tao, Gao Linlin *et al*., 2013. A 457-year reconstruction of precipitation in the southeastern Qinghai-Tibet Plateau, China using tree-ring records. *Chinese Science Bulletin*, 58(10): 1107–1114.

Li Qiang, Liu Yu, Cai Qiufang *et al*., 2006. Reconstruction of annual precipitation since 1686A.D. from Ningwu Region, Shanxi Province. *Quaternary Sciences*, 26(6): 999–1006. (in Chinese)

Liu Jingjing, 2014. Precipitation variations during the last 526 years inferred from tree-ring width on the southern Tibetan Plateau. *Journal of Lanzhou University* (*Natural Sciences*), 50(3): 293–298. (in Chinese)

Liu Yu, An Zhisheng, Ma Haizhou *et al*., 2006. Precipitation variation in the northeastern Tibetan Plateau recorded by the tree rings since 850 AD and its relevance to the Northern Hemisphere temperature. *Science in China Series D Earth Sciences*, 49(4): 408–420.

Qin Ningsheng, Shao Xuemei, Jin Liya *et al*., 2003. Climate change over southern Qinghai Plateau in the past 500 years recorded in Sabina tibetica tree rings. *Chinese Science Bulletin*, 48(22): 2484–2488.

Shao Xuemei, Huang Lei, Liu Hongbin *et al*., 2005. Reconstruction of precipitation variation from tree rings in recent 1000 years in Delingha, Qinghai. *Science in China Ser. D Earth Sciences*, 48(7): 939–949.

Shao Xuemei, Liang Eryuan, Huang Lei *et al*., 2006. A reconstructed precipitation series over the past millennium in the northeastern Qaidam Basin. *Advances in Climate Change Research*, 2(3): 122–126. (in Chinese)

Shi Xinghe, Qin Ningsheng, Shao Xuemei *et al*., 2009. Precipitation change over the past 1000 years recorded in Sabina Tibetica tree rings in Lake Qinghai Basin. *Journal of Lake Sciences*, 21(4): 579–586. (in Chinese)

Tian Qinhua, Zhou Xiuji, Gou Xiaohua *et al*., 2012. Analysis of reconstructed annual precipitation from tree-rings for the past 500 years in the middle Qilian Mountain. *Science China Earth Sciences*, 55(5): 770–778.

Wang Wenzhi, Liu Xiaohong, Xu Guobao *et al*., 2013. Moisture variations over the past millennium characterized by Qaidam Basin tree-ring δ^{18}O. *Chinese Science Bulletin*, 58(32): 3956–3961.

Wang Xiaochun, Zhang Qibin, Ma Keping *et al*., 2008. A tree-ring record of 500-year dry-wet changes in northern

Tibet, China. *The Holocene*, 18(4): 579–588.

Wang Zhenyu, Li Lin, Wang Qingchun *et al*., 2005. Characteristic of precipitation variation in summer season over Qinghai Province in 500 years recorded from tree-rings. *Climatic and Environmental Research*, 10(2): 250–256. (in Chinese)

Xu Guobao, Liu Xiaohong, Qin Dahe *et al*., 2014. Tree-ring $\delta^{18}O$ evidence for the drought history of eastern Tianshan Mountains, Northwest China since 1700 AD. *International Journal of Climatology*, 34(12): 3336–3347.

Yang Bao, Qin Chun, Wang Jianglin *et al*., 2014a. A 3,500-year tree-ring record of annual precipitation on the northeastern Tibetan Plateau. *Proceedings of the National Academy of Sciences*, 111(8): 2903–2908.

Yang Yuhui, Chen Yaning, Li Weihong *et al*., 2012. Climatic change of inland river basin in an arid area: a case study in northern Xinjiang, China. *Theoretical and Applied Climatology*, 107(1/2): 143–154.

Yu Shulong, Yuan Yujiang, Jin Hailong *et al*., 2005. A 379-year July-August precipitation series reconstructed from tree-ring on the midwestern part of the northern slopes of Tianshan Mountains. *Journal of Glaciology and Geocryology*, 27(3): 404–410. (in Chinese)

Zhang Lu, Yuan Yujiang, Wei Wenshou *et al*., 2010. Reconstruction and analysis of the 336-a July and August precipitation series in Nilka County, Xinjiang. *Journal of Glaciology and Geocryology*, 32(5): 914–920. (in Chinese)

Zhang Qibin, Cheng Guodong, Yao Tandong *et al*., 2003. A 2,326-year tree-ring record of climate variability on the northeastern Qinghai-Tibetan Plateau. *Geophysical Research Letters*, 30(14): 1739.

Zhang Qibin, Evans Michael N, Lyu Lixin, 2015. Moisture dipole over the Tibetan Plateau during the past five and a half centuries. Nature Communications, 6: 8062. doi: 10.1038/ncomms9062.

Zhang Ruibo, Wei Wenshou, Yuan Yujiang *et al*. 2009. A precipitation series of A.D. 1396–2005 in Aksu River Basin on the southern slopes of Tianshan Mountains: Reconstruction and analysis. *Journal of Glaciology and Geocryology*, 31(1): 27–33. (in Chinese)

Zhang Tongwen, Yuan Yujiang, Yu Shulong *et al*., 2008. June to September precipitation series of 1481–2004 reconstructed from tree-ring in the western region of Altay Prefecture, Xinjiang. *Journal of Glaciology and Geocryology*, 30(4): 659–667. (in Chinese)

Zhang Yong, Tian Qinhua, Gou Xiaohua *et al*., 2011. Annual precipitation reconstruction since AD 775 based on tree rings from the Qilian Mountains, northwestern China. *International Journal of Climatology*, 31(3): 371–381.