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Temperature and Precipitation Changes in China During the Holocene

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ABSTRACT

We review here proxy records of temperature and precipitation in China during the Holocene, especially the last two millennia. The quality of proxy data, methodology of reconstruction, and uncertainties in reconstruction were emphasized in comparing different temperature and precipitation reconstruction and clarifying temporal and spatial patterns of temperature and precipitation during the Holocene. The Holocene climate was generally warm and wet. The warmest period occurred in 9.6–6.2 cal ka BP, whereas a period of maximum monsoon precipitation started at about 11.0 cal ka BP and lasted until about 8.0–5.0 cal ka BP. There were a series of millennial-scale cold or dry events superimposed on the general trend of climate changes. During past two millennia, a warming trend in the 20th century was clearly detected, but the warming magnitude was smaller than the maximum level of the Medieval Warm Period and the Middle Holocene. Cold conditions occurred over the whole of China during the Little Ice Age (AD 1400–AD 1900), but the warming of the Medieval Warm Period (AD 900–AD 1300) was not distinct in China, especially west China. The spatial pattern of precipitation showed significant regional differences in China, especially east China. The modern warm period has lasted 20 years from 1987 to 2006. Bi-decadal oscillation in precipitation variability was apparent over China during the 20th century. Solar activity and volcanic eruptions both were major forcings governing the climate variability during the last millennium.

Key words: proxy data, temperature, precipitation, China, holocene

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1. Introduction

It is now widely accepted that increasing concentrations of greenhouse gases in the atmosphere are causing higher global atmospheric temperatures (Oeschger, 2000; Issar, 2003). However, the pace and magnitude of future change, especially regional patterns, remains very uncertain (IPCC, 2001; Valdes, 2003). Although predictions of future climate change are almost entirely model-based, paleoclimate data are essential for both checking the predictions of climate models and characterizing the natural variability of the climate system (Webb III et al., 1993; Bradley et al., 2003). The Holocene as the present interglacial is of special interest because it contains time-slice analogs of climate warmer than present such as the Medieval Warm Period (MWP, AD 900–1300, Mann, 2002) and the middle Holocene, and because its temporal overlap with the present day allows direct comparison of instrument records and longer-term proxy data (Webb III et al., 1993; Oldfield, 2003).

Over recent decades, extensive investigations into the Holocene climate of China were conducted and a lot of high quality data became available. We write this review with several goals: (1) to provide an updated synthesis of millennial-scale climate changes during the Holocene in China; (2) to highlight temperature and precipitation changes on decadal to centennial timescales during the last two millennia; (3) to provide a brief review of temperature and precipitation

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variability on interannual to decadal timescales during the instrumented times; and (4) to present some model-data comparisons. A sketch map of China and cited locations of this paper is shown here for easily reading (Fig. 1)

2. Temperature and precipitation during the Holocene

2.1 *Temperature (Cold/Warm)*

The Holocene began in 11.5 cal ka BP (calendar years) or 10.0 ^{14}C ka BP (^{14}C years). This warm epoch was preceded by the Younger Drays cold period in most areas of the Northern Hemisphere, especially the North Atlantic Basin. Paleoclimatic data of China showed a similar result (Wang et al., 1994, 1996; Yang et al., 1997). The Holocene climate in China was generally warm, exhibiting the main characteristics of the interglacial climate. Having synthesized a series of pollen and other proxy data, Shi et al. (1992) indicated that the warmest period, the so-called Holocene megathermal, occurred in 8.5–3.0 ^{14}C ka BP. Temperatures in the Holocene megathermal were about 1°C–5°C higher than the present in China. However, there existed latitudinal differences in the amplitude of temperature variations. The temperature difference between the Holocene megathermal and the present was 3°C–4°C in northern China, whereas it was 1°C–2°C in southeast China. Wang et al. (2001) reconstructed the mean temperature series of China for the Holocene with 250-yr time resolution. This reconstruction was derived from an area-weighted average of ten regional temperature series using regional area size as weights. It showed that temperatures in 7.5–7.0 and 6.0–5.5 ^{14}C ka BP were about 2°C higher than the present. It is not unexpected that somewhat discrepancy in the amplitude of temperature variation exists between results from Shi et al. (1992) and Wang et al. (2001), since the whole of China was used as the spatial domain in Wang et al. (2001) reconstruction whereas the regions were considered separately in the work of Shi et al. (1992). Additionally, this discrepancy could be partially attributed to the asynchronous occurrence of the maximum temperature between regions, as suggested by He et al. (2004). They found that the Holocene megathermal began and terminated earlier in high-altitude regions of west China than at lower elevations in east China. And the amplitude of the temperature variations was smaller in the east. The Holocene megathermal was then followed by a cooling trend in the Late Holocene.

The Holocene was once viewed as climatically stable, but detailed and well-dated paleoclimate records now indicate that the Holocene climate was punctuated by several widespread millennial-scale cold events (e.g. Bond et al., 1997; deMenocal et al., 2000). These events recurred roughly every 1500±500 years (Table 1). The Little Ice Age (LIA) was the most recent of these millennial-scale cold events, which was numbered as event “0” by in Bond et al.’s (1997) chronology of Holocene cold events. The earliest one numbered as events “8” occurred in 11.1 cal ka BP. In China, Shi et al. (1992) noted that there were a series of cold events superimposed on a long-term orbitally-forced pattern of temperature change in the warm Holocene. They occurred in 8.7–8.5, 7.3, 5.5, and 4.0 ^{14}C ka BP (≈9.6–9.6, 8.1, 6.2, and 4.4 cal ka BP, respectively). These events likely correspond to cold events 6–3 defined by Bond et al. (1997). The cold events were apparent in ice cores on the Tibetan Plateau (Table 1; Yao and Shi, 1992; Thompson et al., 1997).

2.2 *Precipitation (Dry/Wet)*

Evidence from pollen records, archives of lake levels, and loess records suggested that China generally experienced wet conditions during the Holocene (Shi et al., 1992). However, the Holocene precipitation maximum (or summer monsoon maximum) could have been asynchronous through regions in China (An et al., 2000; He et al., 2004). The review of proxy data from 45 sites reveals that summer monsoon precipitation reached a maximum at different time in different zones within China (An et al., 2000). The precipitation maximum occurred in 10–7 ^{14}C ka BP over North China, and 7–5 ^{14}C ka BP in the middle and lower Yangtze River valley. The precipitation peak in northeastern China came in as early as about 10.0 ^{14}C ka BP, and along the South China coast as late as 3.0 ^{14}C ka BP. They interpreted this regional shift in the maximum precipitation belts as a response of the east Asian summer monsoon to changing seasonality related to orbital forcing in the Holocene.

Instrumental observations demonstrated that precipitation increased in North China as well as the Tibetan Plateau if the summer monsoon was stronger than normal, whereas it decreased along the middle and lower Yangtze River valley when the summer monsoon intensified (Guo et al., 2003). Precipitation increased in south China as the northward extension of ITCZ (The Intertropical Convergence Zone) in response to the strong summer monsoon. Recently, a series of studies provided high-resolution paleoclimate records. These records show humid conditions or high precipitation during the Early Holocene (Table 2). Most of the proxy data outlined in Table 2 are located in the areas where precipitation is positively correlated to the monsoon intensity. Therefore, an increase of humidity or precipitation in the Early Holocene can be

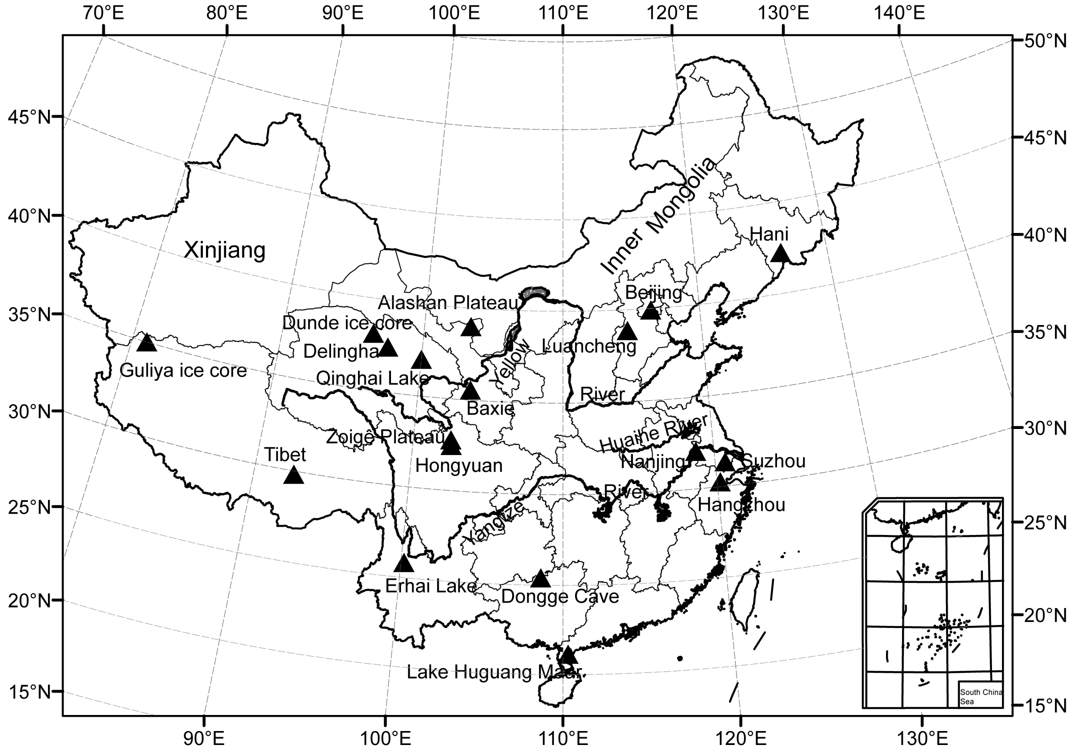

Fig. 1. The sketch map of China (the cited locations in the paper are marked with black triangles).

Table 1. Cold events over the North Atlantic and monsoon failures in China (cal ka BP).

Site (Region)	Climate	0	1	2	3	4	5	6	7	8	Authors
North Atlantic	cold	0.4	1.4	2.8	4.3	5.9	8.2	9.5	10.3	11.1	Bond et al., 1997
Guliya ice core	cold	0.9	1.7	3.4	4.0	5.5	8.3	9.0	10.1	11.2	Thompson et al., 1997
Dunde ice core	cold	0.4	1.5	3.0	4.0	5.2	8.8	9.7			Yao and Shi, 1992
Inner Mongolia	dry	0.4	1.7	3.0	4.2	6.0	8.6	9.3	10.5	11.4	Chen et al., 2003b
Zoigê	dry	0.3	1.5	2.8	4.4	5.9	8.2	9.5	10.2	11.3	Zhou et al., 2002
Hongyuan	dry	0.3	1.5	2.8	4.1	5.9	8.3	9.5	10.4	11.2	Hong et al., 2005
Guilin	dry	0.5	1.6	2.7	4.4	5.5	8.3	9.2	10.8	11.2	Wang et al., 2005; Dykoski et al., 2005
South China Sea	dry	0.3	1.2	3.1	4.3	6.0	8.3	9.5			Wang et al., 1999

Table 2. Climate humid periods in the early Holocene.

No.	Site (Region)	Location	Humid period in cal ka BP	Authors
1	Hani	42°13′N, 126°31′E	8–11	Hong et al., 2001
2	Alashan Plateau	39°N, 103°20′E	7–11	Chen et al., 2003a
3	Qinghai Lake	37°N, 100°E	7.5–11	Zhou et al., 2006
4	Hongyuan	32°46′N, 102°30′E	5–11	Hong et al., 2005
5	Zoigê Plateau	32°41′N, 102°32′E	5–11	Zhou et al., 2002
6	Tibet	29°49′N, 92°33′E	5–11	Tang et al., 2000
7	Erhai Lake	25°50′N, 100°11′E	6–8	Zhou et al., 2006
8	Dongge Cave	25°17′N, 108°5′E	5–11.5	Dykoski et al., 2005
9	Lake Huguang Maar	21°09′N, 110°17′E	8–11	Yancheva et al., 2007
10	South China Sea	20°07′N, 117°23′E	8–11	Wang et al., 1999

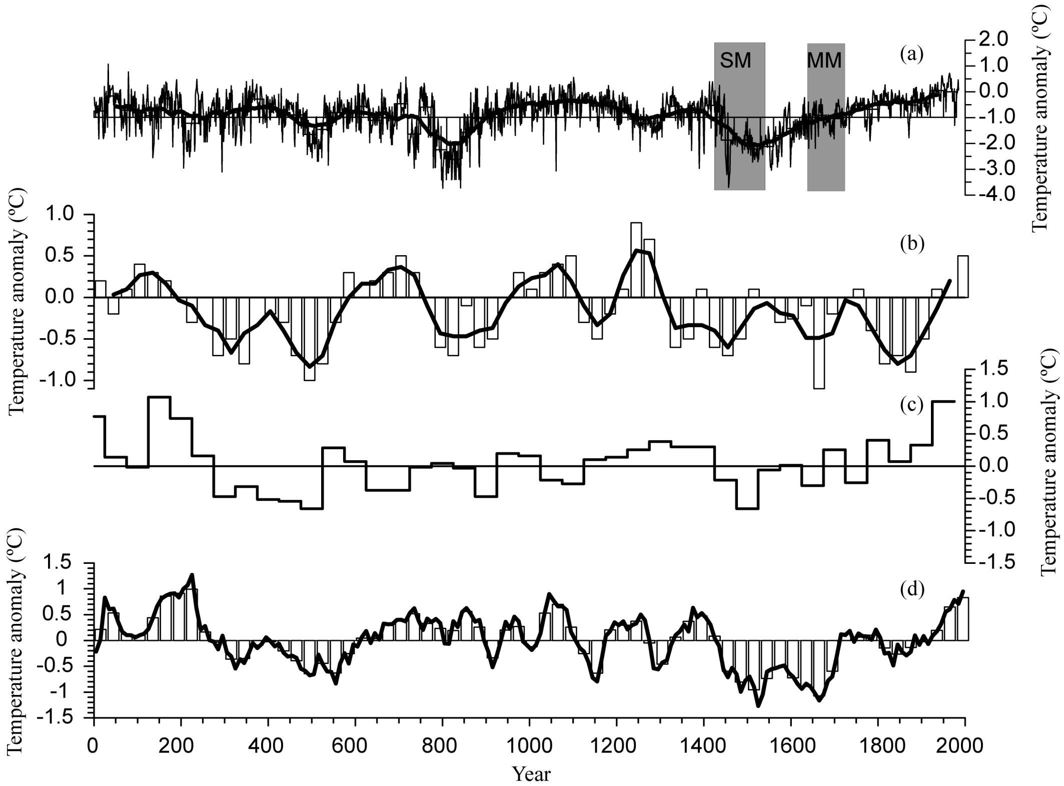

Fig. 2. The reconstructed temperature series during the last 2000 years in China derived from various historical climate proxy data. (a) summer temperature (May–Aug.) in Beijing by Tan et al. (2003), slim line: annual temperature, heavy line: 10-year resolution, bar: temperature change with 30-year resolution, SM: Spörer Minimum (AD 1420–1530), MM: Maunder Minimum (AD 1645–1715); (b) Winter half year temperature in east China at 30-year time resolution by Ge et al. (2003); (c) temperature change at 50-year resolution in the whole Tibetan Plateau by Yang et al. (2003); (d) Weighted temperature reconstruction over China by Yang et al. (2002), line: 10-year resolution, bar: 30-year resolution.

attributed to the intensification of the summer monsoon, and thus the high summer insolation. Again, the longer-term and more gradual orbitally-driven pattern of summer monsoon change was punctuated by a series of monsoon failures (Table 1).

Model simulations indicated that the summertime insolation was the primary driver of the Holocene Asian monsoon dynamics on the millennial-scale (e.g., Liu et al., 2003). However, orbital forcing alone is not sufficient to explain all fluctuations in monsoon change, especially these monsoon failures. Feedback associated with changes in SSTs and land surface cover should be involved (Texier et al., 2000; Jin et al., 2006). In a recent simulation, an atmospheric general circulation model (AGCM) and an oceanic general circulation model (OGCM) were asynchronously coupled to simulate the Mid-Holocene climate (Wei and Wang, 2004). Compared with a simulation driven by orbital forcing only, more precipitation and a stronger summer monsoon over east Asia were observed in the simulation with orbital forcing and changing SSTs. The results agree well with the reconstructed data (Wei and Wang, 2004). Jin et al. (2006) investigated the response of the east Asian monsoon to changes in snow and glaciers over the Tibetan Plateau during the Mid-Holocene using a global atmospheric general model. The simulations show a significant decrease in precipitation over the south and east Asian continent but an increase in rainfall along the southeast coast of Eurasia in boreal summer, suggesting that the feedback of snow and glaciers over the Tibetan Plateau weaken the Asian summer monsoon.

3. Temperature and precipitation over past two millennia

The past two millennia encompass a period when natural forcing dominated and an interval when anthropogenic forcing became significant. It has received increasing concern in recent decades due to its importance in better understanding natural forcing mechanisms and response of climate systems to anthropogenic forcing (Eddy, 1992; IPCC, 2001). Furthermore, it is most relevant to assessing the potential uniqueness of recent climate changes and the projected changes in the 21st century (Jones and Mann, 2004).

3.1 *Temperature (Cold/Warm)*

Chu (1973) was the first to conduct the reconstruction of temperature using historical documents and other proxy data in China. Since his pioneering work, numerous reconstructions of temperature have been generated for China from a variety of data sources and methodologies (e.g., Zhang, 1980; Wang and Wang, 1990; Wang, 1991; Wang et al., 1998a; Wang and Gong, 2000). However, most of them focused on the past millennium. In recent decades, some records longer than 1000-yr became available. Ge et al. (2003) reconstructed winter half-year (October to April) temperatures at 10- to 30-yr resolution from phenological cold/warm events recorded in Chinese historical documents for the past 2000 years in the central region of east China. Yang et al. (2002, 2003) established China-wide temperature composites at 10-yr resolution and a temperature series at 50-yr resolution on the Tibetan Plateau for the last 2000 years by combining multiple proxy data from ice cores, tree rings, lake sediments, and historical documents. Tan et al. (2003, 2004) reconstructed a 2650-yr (BC 665–AD 1985) temperature series of the warm season (May to August) in Beijing. It was derived from a correlation between the thickness of annual layers in a stalagmite and observed temperature.

Figure 2 shows a comparison of temperature reconstruction in China over the last two millennia. The warm season temperature record in Beijing (Fig. 2a) revealed a cyclical alternation of warm and cool periods on the centennial-scale throughout the past two millennia. The MWP is apparent in this record. As suggested by Tan et al. (2003), the warm-season temperature in Beijing is strongly linked to the variability of solar forcing. However, the temporal pattern of the winter half-year temperature record over east China (Fig. 2b) is different from the warm-season temperature record in Beijing in most intervals over the past two millennia. It is more similar to that of annual temperature record on the Tibetan Plateau (Fig. 2c), especially during some intervals such as AD 0–800, AD 1000–1300, and AD 1500–2000. The MWP in both records is not as apparent as the warm season temperature record in Beijing. It also is not evident in China as a whole (Fig. 2d). The highest winter half-year temperature occurred during the period of AD 1230s–1280s when it is about 0.7°C–0.9°C higher than the present (referenced to the average of 1951–1980) over east China, whereas AD 100–250 is the warmest period for the Tibetan Plateau and China as a whole. The increase of temperature during the 20th century is significant in these records. However, it is evident that 20th century warming still lies in the range of natural temperature variability in China. During the LIA characterized by cold conditions, consistent low temperatures were observed only in its early part (AD 1550–1700) in these records. No significant decline in temperature occurred during its late part (AD 1700–1850) in these records except the winter half-year temperature over east China. East China experienced the coldest winter half-year of the past 2000 years in AD 1750–1900. It is worth noting that these reconstructions are clearly not identical, although they have much in common. One explanation for the differences may lie in the geographical distribution of reconstructions and the size of spatial domain represented by each reconstruction. In Fig. 2, Ge et al. (2003) and Yang et al. (2003) reconstructions are from east and west China respectively. Yang et al.'s (2002) reconstruction has a large spatial domain (all of China), whereas Tan et al.'s (2003) reconstruction is a record of an individual region in east China. Another reason for the differences may be because each reconstruction represents a somewhat different season. Warm season temperature was used in Tan et al. (2003) reconstruction, whereas the temperature parameter used in Ge et al. (2003) reconstruction is winter half-year temperature and it is annual temperature in Yang et al. (2002, 2003) reconstruction. Additionally, the different proxy data used in reconstructions may contribute to the differences between reconstructions. In these four reconstructions, a single proxy such as historical documents (Ge et al., 2003) and speleothems (Tan et al., 2003), and multi-proxy combinations (Yang et al., 2002, 2003) were used.

Available high resolution natural archives such as ice cores, tree rings, and speleothems are few in China, especially in east China. However, historical data is particularly abundant in China due to the fact that more governmental archives ("Official History") have survived and that the compilation of local gazettes had become a more common practice for counties and districts since the Ming Dynasty (Zhang, 1988). A great number of government archives and local gazettes thus provide abundant data resources with regard to weather and climate in historical times (e.g., Wang and Zhao, 1981; Zhang, 1988; Wang and Zhan, 1991; Wang and Zhang, 1992; Wang et al., 1992; Liu et al., 2001). Historical documentary data have the advantage of frequently being strongly related to a single climatic variable, while other proxy data such as tree rings, ice cores, and speleothems reflect a complex interaction of several climatic factors that are often difficult to isolate (Guiot et al., 2005). The disadvantages of documentary proxies, however, are the subjectivity of the observer, the missing time periods, and their temporal extent (Pfister, 1999). Much effort has been made in the last few decades to reconstruct temperature during the past two millennia over China using a variety of historical documents by Chinese researchers (e.g., Zhang, 1980; Wang and Wang, 1990; Ge et al., 2003). However, these reconstructions are not clearly identical, as mentioned above. Critical questions arising from such differences and the disadvantages of documentary proxies are: (1) What results in the discord between different reconstructions? (2) What temporal resolution would be suitable for reconstruction using historical information with missing intervals? and (3) How reliable are these document-based reconstructions? One feasible means of addressing these questions is to compare the temperature series reconstructed by different studies using historical documents, and to validate these reconstructions against temperature series derived from natural archives as conducted by Ge et al. (2007). In that comparative study, 14 temperature series reconstructed from historical documents by different studies and two temperature series derived from natural archives were examined. It is found that the temperature series by different studies are highly correlated. The closer the reconstructed regions are, the higher their correlation is. This fact implies that the differences of document-based reconstructions are mainly caused by the regional differences of climate change. They noted that the temporal resolution significantly affected the differences of reconstructions, and Chinese historical documentary data would provide more confident and consistent reconstructions of temperature at 30-yr temporal resolution. Their study also demonstrated the similarity between the reconstructions derived from historical documents and natural archives, suggesting that these document-based reconstructions are reliable.

Additionally, comparisons of model simulation results with empirical temperature reconstructions were also conducted in China for understanding the factors governing climate changes in past millennia and improvement of model. Liu et al. (2005) compared the reconstruction of winter half-year temperature by Ge et al. (2003) with the output of a millennium simulation by ECHO-G, a global atmosphere-ocean coupled climate model. The simulation was driven by time-varying external forcing including solar radiation, volcanic eruptions, and greenhouse gas concentrations (CO_2 and CH_4). The MWP, the LIA, and the modern warming period after AD 1900 were well recognized in both simulated and reconstructed temperatures. The amplitudes of simulated temperature anomalies are comparable with those in the reconstructions during the modern warming period and the LIA, particularly the Maunder minimum (AD 1670–1710). Both simulated and reconstructed temperature anomalies reach their minima in phase during the Maunder minimum. The model simulation results indicate that variations in solar radiation and volcanic activity are the main factors controlling regional temperature change during the last millennium, while the concentration of greenhouse gases is the major cause of 20th century warming.

3.2 *Precipitation (Dry/Wet)*

In China, high-resolution proxy data of precipitation are mainly from historical documentary records and natural archives such as tree rings, ice cores, and speleothems. Ice cores are limited in the Tibetan Plateau, whereas most tree ring chronologies are restricted to the western part of China. Only a few proxy data from tree rings and speleothems exist over east China. However, proxy data from historical documents are abundant over east China, as mentioned above. Historical data from China, mainly compiled from county (Xian) and district (Fu or Zhou) gazettes and archives, provide both temporal and spatial information of precipitation conditions in historical times (Shen et al., 2007).

In the 1970s, a network of drought/flood (D/F) index consisting of 120 regions over China and spanning the last five centuries (AD 1470–1950) was developed (Academy of Meteorological Science of China Central Meteorological Administration, 1981). As a measure of precipitation in the main rainy season (Zhang, 1988), this index uses five grades, 5—very wet, 4—wet, 3—normal, 2—dry, 1—very dry, to describe precipitation conditions. Among 120 time series of D/F index, 63 time series in regions with relatively abundant historical documents were extended back to BC 137 (Zhang, 1996). Recently, Zheng et al. (2006) developed a new dataset of D/F index consisting of 48 regions over east China on the base of datasets mentioned above. This new dataset was then used to analyze decadal to centennial precipitation variability over east China (Fig. 3b) and in its three divisions, the North China Plain (34°–40°N approximately), the Yangtze River and Huaihe River valleys (31°–34°N approximately), and the south of the Yangtze River area (25°–31°N approximately) (Fig. 1). On the centennial scale, four dry epochs (500s–870s, 1000s–1230s, 1430s–1530s, and 1920s–1990s) and three wet epochs (880s–990s, 1240s–1420s, and 1540s–1910s) exhibited in east China. Each epoch was superposed by multi-

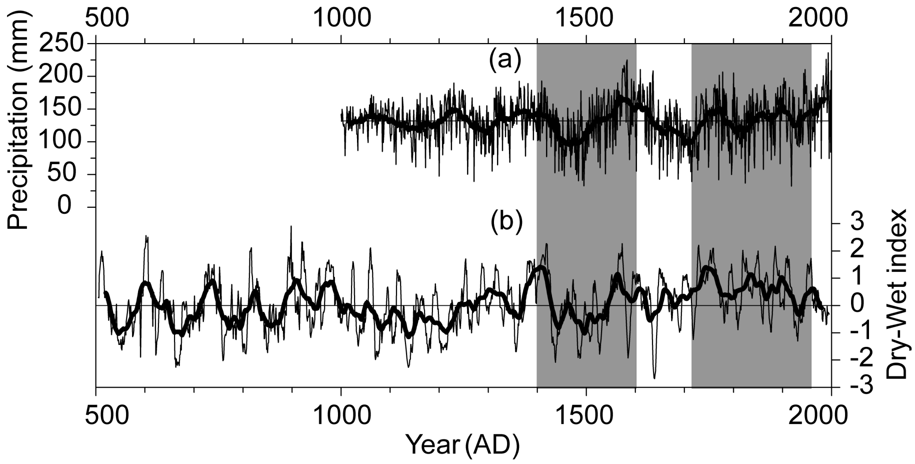

Fig. 3. The reconstructed precipitation (dry/wet) series from tree rings in western China during the last 1000 years (a, Shao et al., 2004) and historical documents in east China during the last 1500 years (b, Zheng et al., 2006). The consistent increasing or decreasing change trend is marked by the shaded area; the heavy line: 31-year running average smoothing.

decadal fluctuations. They noted remarkable regional differences in precipitation variations among three divisions during the past 1500 years. For example, opposite trends existed between the south of the Yangtze River area and the Yangtze River and Huaihe River valleys during the 11–13th centuries, and between the North China Plain and the south of the Yangtze River area after the 16th century. Their data also showed 16 drought and 18 flood events persisting for multiyear to decades in east China. The most severe drought event occurred from 1634–1644. Droughts dominated in 12–14th centuries, whereas floods were common after the middle of 17th century. Floods during the 20th century were comparable in intensity to those during historical times, but the droughts were usually less severe.

Despite the fact that the D/F index provides some insights into precipitation variability, it is not as useful as other proxy data in detailing truly large-scale precipitation variations and model-data comparisons, as it is a qualitative rather than a quantitative reconstruction of precipitation. In the most recent several years, some quantitative reconstructions of precipitation using the detailed snow and rainfall archives, e.g., Qing-Yu-Lu (Clear and Rain Records) and Yu-Xue-Fen-Cun (rainfall infiltration and snowfall depth), became available in north China and the mid-lower Yangtze River valley, although only 300 years were recovered by these reconstructions. For example, Zhang and Liu (2002) and Zhang et al. (2005) reconstructed annual and seasonal precipitation in Beijing (1724–1903), Nanjing (1723–1798), Suzhou (1736–1806), and Hangzhou (1723–1773) using Clear and Rain Records. The quantitative reconstructions were used to trace the Meiyu (plum rain) activity for the 18th century in the lower reaches of the Yangtze River (Zhang and Wang, 1991). It is found that the early Meiyu, which is characterized by excessive rainfall, occurred frequently during the period from the 1740s–1770s. Recently, Ge et al. (2005) and Zheng et al. (2005) conducted a rainfall infiltration experiment following the Yu-Xue-Fen-Cun measurement to build an empirical relationship between the rainfall and the infiltration depth for the calibration of historical records into quantitative estimates of precipitation. Precipitation series back to AD 1736 were reconstructed for Hebei, Weihe, Jinnan, and Shandong in the middle and lower reaches of the Yellow River. The quantitative reconstructions indicated an abrupt shift from high to low precipitation around 1915. This shift might be associated with changes in large-scale atmospheric circulations such as the Pacific decadal oscillation (PDO).

In west China, more than 20 precipitation (dry/wet) series were generated from various proxy records (ice cores, lake sediments, tree-rings, and speleothems) located in Xinjiang, Xizang, Qinghai, and Shaanxi in recent decades (Zhang and Wu, 1992; Duan et al., 2002; Liu et al., 2004; Shao et al., 2006). Among them, the longest record is a tree ring reconstruction of annual precipitation since 515 BC for Dulan in northeast Qinghai (Sheppard et al., 2004). This record indicated that relatively dry conditions occurred during AD 51–375, 426–500, 526–575, 626–700, 1100–1225, 1251–1325, 1451–1525, 1651–1750, and 1801–1825. Relatively wet conditions occurred during AD 376–425, 576–625, 951–1050, 1351–1375, 1551–1600, and the present. Similar temporal patterns of precipitation were also found in other long tree ring reconstructions for the same region (Zhang et al., 2003) and adjacent regions (Shao et al., 2004, 2006). The reconstruction of annual precipitation for Delingha (about 100 km northwest to Dulan, Fig. 3a) reveals two significant wet periods in AD 1520–1633 and AD 1933–2001, and two major dry periods in AD 1429–1519 and AD 1634–1741. Shao et al. (2004, 2006) also found that the amplitude of precipitation fluctuation was small (about 15 mm) during the interval prior to AD 1430, whereas it reached as large as 30 mm during the period of AD 1430–1850. Using the Empirical Orthogonal Function, Wang et al. (2002a) analyzed 17 series of proxy precipitation from tree rings (11 series), historical data (4 series), and ice core (1 series) in west China to study precipitation changes in this region during the last 400 years. The first Empirical Orthogonal Function (EOF1) showed a significant dry period in the 17th century, especially in its first half, consistent with the results of Shao et al. (2004, 2006). An increase of precipitation was found in the second half of the 20 century, especially during the last 30 years.

A critical question often asked in the studies of climate change in China, one of the most typical monsoon climate countries in the world, is: what moisture conditions, i.e. dry or wet, accompany the warming? The answer for this question seems to vary in both space and time. A notable increasing trend of precipitation was recorded after 1970s in west China, suggesting a warm-wet climate (Shi et al., 2003), whereas a warm-dry climate was found in east China (Wang et al., 2001). However, this relationship between precipitation and temperature in west and east China does not seem constant through time (Fig. 3). Coherent variability in precipitation was also found during the periods of AD 1400s–AD 1600s and AD 1710s–AD 1960s.

4. Temperature and precipitation since AD 1880

Global warming is an important issue in studies of climate change during the last century. To estimate accurately the warming rate, National Climate Center (NCC) has developed a dataset of monthly temperature and precipitation from 1951 to the present. It consists of 160 stations, covering the most land areas of China. However, 50 years is not long enough to evaluate the warming; it is essential to extend records back as early as possible. Wang et al. (1998b) extended records of annual mean temperature for ten regions back AD 1880 by combining the instrumental observations with the proxy data. Those ten regions of China include Northeast, North, East, South, Taiwan, central, Southwest, Northwest, Xinjiang, and Tibet. A mean temperature series for China was developed by an area-weighted average of the ten regional temperature series, so the impact of the bias associated with the spatial coverage of the data was significantly reduced. The errors of this series mainly came from proxy data, since ice core, tree ring, and documentary data used to fill the gaps of instrument observations have their uncertainties in temperature reconstructions. Tang and Ren (2005) constructed seasonal mean temperature series for China for the last century using instrumental observations. The mean maximum and minimum daily temperature were used instead of the average value of 3 or 4 times of measurements per day to avoid the bias with different daily observational times. The shortcoming of this series was the inconstant data coverage, because instrumental records in the early 20th century covered only about one-third of the mainland area of China. Recently, the mean temperature series of China for the last century was worked out by Wen et al. (2006) based on the dataset of the Climate Research Unit (CRU[a])at East Anglia University of UK, which was a new monthly temperature and precipitation dataset at $0.5° \times 0.5°$ grid points by statistical interpolation to instrument observations. This series provided a complete set of grid point temperature anomalies without any missing data and change of data spatial coverage. However, the two shortcomings of CRU dataset should be taken into consideration. One is the obscurity of temperature information in west China, especially over the Tibetan plateau in the first half of the 20th century. The other is the reduced extreme value of temperature anomalies as the statistical interpolation is used.

Three series of annual mean temperature for China are shown in Fig. 4. These series are highly correlated, as suggested by their correlation coefficients significant to the 99.9% confidence level, although they were derived from different datasets and different techniques. There existed a period of low temperature from the end of the 19th to the early 20th century. The temperature increased afterward to reach a relatively stable period of high temperature in the 1940s. The temperature lower than that of the reference years occurred in the 1960s and 1970s. Significant warming began in the middle of the 1980s. Therefore, the modern warm period in China just covers the last 20 years from 1987 to 2006.

In China, spatial coverage of long precipitation observations was usually smaller than that of tempera-

[a]http://www.cru.uea.ac.uk/~timm/grid.CRU-TS-2-1.html

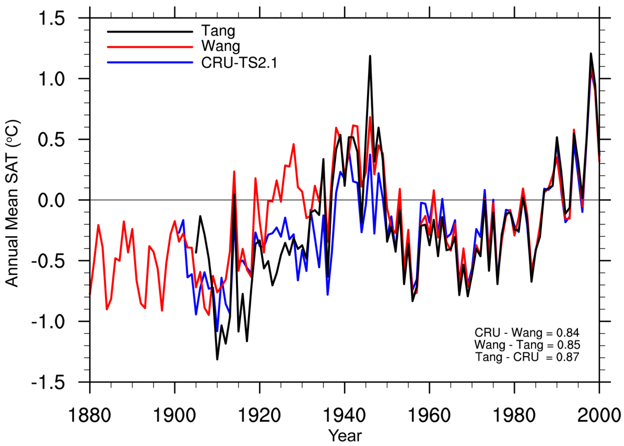

Fig. 4. Annual mean temperature series of China since AD 1880 (average of 1971–2000 as referenced value). Correlation coefficients between them are also shown.

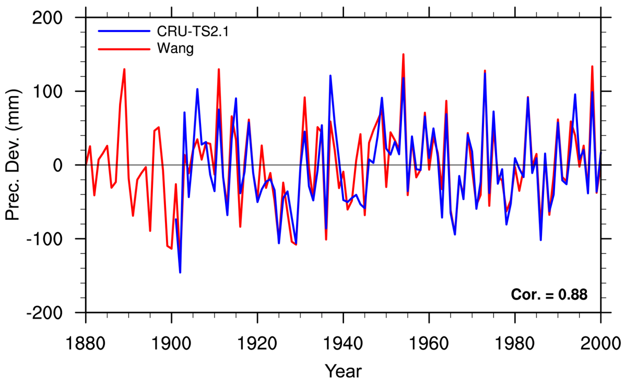

Fig. 5. Mean annual precipitation of China in the area east of 105°E.

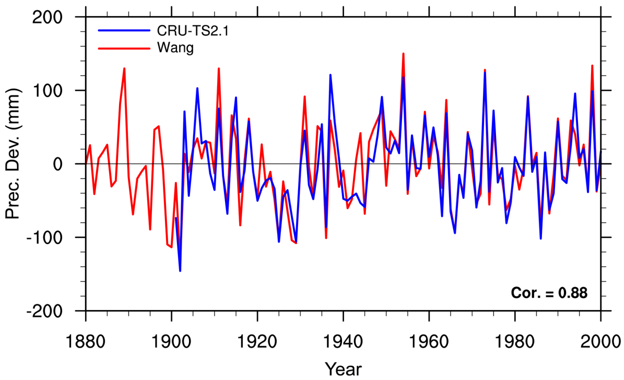

Fig. 6. Mean annual precipitation of China.

ture. Wang et al. (2000) developed a precipitation dataset since 1880 for east China, which consisted of 35 stations. This dataset was then expanded to 71 stations[b] (referred hereafter as Wang). In Fig. 5, the red line shows anomalies of area-weighted average annual precipitation for east China (east of 105°E) based on annual precipitation at 1° × 1° grid points interpolated from the dataset of 71 stations. The blue line gives the anomalies of annual precipitation for the same region calculated from CRU dataset (Wen et al., 2006). Noting that the red line was derived from seasonal precipitation, i.e., March to May, June to August, September to November, and December to February, so the annual total precipitation was the summation from December to November of the following year. It is different from the annual precipitation of CRU, which is the summation from January to December. Nonetheless, there is a very good agreement for interannual variability between the two series. The correlation coefficient (0.88) between their common parts (the 20th century) is significant to the 99% confidence level ($r = 0.88$). Two series were almost identical since 1951, when plenty of observations were available. Some discrepancies in the period of the first half of 1940s could be attributed to the impact of scarce data during World War II.

The precipitation anomalies (referenced to the observational mean value of 1971–2000) for China derived from the NCC dataset and CRU dataset, respectively, are shown in Fig. 6. The correlation coefficient between the two series is 0.93 for the second half of the 20th century. The CRU series also provided the information about precipitation over the whole of China in the first half of the 20th century. The major droughts in the 1920s and 1940s widely described in Chinese literature and journals were identified well in CRU series. Plentiful precipitation occurred in the 1910s, 1930s, 1950s, 1970s, and 1990s, exhibiting a bi-decadal oscillation of precipitation during the 20th century in China (Wang et al., 2002b).

5. Conclusions and discussions

We have presented a review of the Holocene climate studies in China addressing temperature and precipitation changes on interannual to millennial-scales during the Holocene and past two millennia. Generally, the Holocene witnessed warm and wet conditions in China. The warmest period occurred in about 8.5–5.5 ^{14}C ka BP (≈9.6–6.2 cal ka BP). It was followed by a cooling trend in the Late Holocene. High-resolution and well-dated proxy data available recently show that

[b]The result of the Key Project of National Science Foundation: *Study of Climate Variability over the Globe and in China During the 20th Century*, which were implemented by Wang Shaowu et al. during 1996–1999.

a period of maximum monsoon precipitation started at about 11.0 cal ka BP and lasted until about 8.0–5.0 cal ka BP. Although both reviews (An et al., 2000; He et al., 2004) suggested the occurrence of an asynchronous Holocene optimum in regions of east China as well as between west and east China, this time-transgressive pattern is not clear in these new records. Therefore, more well-dated and summer monsoon precipitation sensitive proxy records are necessary in China, especially south China and the middle-lower Yangtze River valley, for making this pattern clear. The long-term orbitally-forced patterns of both temperature and precipitation change during the Holocene were punctuated by a series of millennial-scale cold or dry events. Although work to date has revealed a coherent pattern of these events, more well-dated and high-resolution proxy records as well as model simulations are needed to develop a detailed picture of these events so that we may understand their temporal and spatial patterns and the mechanisms for them.

Both reconstruction and model simulations suggested that the temperature has been rising rapidly during the twentieth century in the context of the past 2000 years, especially for the most recent decades. During the past two millennia, the MWP is not as apparent as LIA in most of the records. Abundant historical documentary data over east China provide reliable reconstructions of temperature and precipitation, although temporal resolution significantly affects the quality of reconstruction, especially those prior to AD 1000 due to a lot of data gap (Ge et al., 2007). Additionally, reconstructions derived from different proxy data may reflect different seasons and different time-resolution, so direct comparisons between them should be conducted with caution.

Proxy data from historical documents, tree rings, ice core, and speleothems reveal that there were many major droughts and floods persisting for multi-year periods to decades in both west and east China during the past two millennia. However, it is extremely difficult to present the spatial patterns of these droughts and floods, especially for west China and intervals prior to AD 1470 due to less available proxy data and the uneven distribution of proxy data. During the 20th century, precipitation in China showed a bi-decadal oscillation of precipitation. And precipitation over west and east China showed a dipole pattern after 1970s. A warm-wet climate occurred in west China, but a warm-dry climate occurred in east China.

Overall, although some annual to decadal resolution temperature and precipitation series were reconstructed for the last two millennia, and some high-resolution and well-dated proxy records for the Holocene became available during the last decades, more records are needed to develop a detailed picture of temporal and spatial patterns of temperature and precipitation in China. More model simulations and more model-data comparisons are necessary to understanding the mechanisms for the climate variability on different time scales.

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