Temporal and spatial variations of climate in China during the last 10 000 years

Zhaodong Feng, L.G. Thompson, E. Mosley-Thompson and Tandong Yao

The Holocene 1993 3: 174
DOI: 10.1177/095968369300300210

The Holocene 3,2 (1993) pp. 174–180

Temporal and spatial variations of climate in China during the last 10 000 years

Zhaodong Feng[+*], L.G. Thompson[°], E. Mosley-Thompson[°] and Tandong Yao[†]

([+] Department of Geography, Lanzhou University, Lanzhou, People's Republic of China; [°] Byrd Polar Research Center, Ohio State University, Columbus, OH 43210, USA; [†] Lanzhou Institute of Glaciology and Geocryology, Lanzhou, Peoples' Republic of China)

Received 1 January 1992; revised manuscript accepted 30 October 1992

A HOLOCENE RESEARCH REVIEW

Abstract: Archaeological, geological, historical, tree-ring and instrumental data indicate that the last 10 000 years were characterized in China by climatic variations at various temporal and spatial scales. The period from 10 000 to 9000 BP was one of increasing temperature. The Holocene 'Optimal Period' occurred approximately between 9000 and 3000 BP, within which there were two major cool episodes around 7300 amd 5700 BP and one minor cool episode around 4500 BP. During the cool period from 3000 BP to AD 1900 (Neoglaciation) three warm episodes occurred about 2700–2000, 1400–1000 and 800–700 BP. The last millennium was characterized by warming in the first half and cooling in the second half. During the most recent 500 years ('Little Ice Age'), relatively warm episodes occurred about AD 1520–1650, 1720–1840, and 1890–1945. Over the long term, climate appears to have changed synchronously from the east to the west and from the south to the north; but it has changed asynchronously over the shorter term.

Key words: climatic change, proxy evidence, periodicity, spatial variation, Holocene, China.

Introduction

The study of climatic change on prehistorical and historical timescales provides a valuable perspective for interpreting the natural trend of climatic variability of the past, and a database for assessing present and future climates under intensive and extensive human impacts. Because only a 100–150-year instrumental record is available, it is necessary to resort to various climatic proxies (e.g., geological and archaeological data, tree rings, personal diaries, official documentation, family genealogical records, etc.) to reconstruct past climates. In this review paper, the climates of the past 150 years are based on instrumental records which were presented in the proceedings of the 1977 Conference on Prediction of Long Term Climate Changes (see Meteorological Bureaux, 1977). The climates of the past 500 years are derived from detailed historic records and tree ring data. Historic records and archaeological data are the sources for reconstructing the climates of the past 5000 years. Archaeological and geological data are used as climatic proxies to extend the climatic curve from 5000 to 10 000 BP.

* *Present address:* Lamont-Doherty Geological Observatory, Columbia University, NY 10964, USA

The climate of China is characterized by three major features (Zhao, 1981). First, the monsoon dominates with a significant change or reversal of wind direction between winter and summer, as well as seasonal variation of precipitation according to whether the maritime monsoon advances or retreats. Secondly, climatic continentality is rather pronounced, with high summer temperatures, low winter temperatures, and a large annual range. Thirdly, there are many climatic types in China, ranging from a subpolar climate on the Tibet Plateau to a subtropical climate along the southern coasts. All these climatic characteristics are a product of the interaction of major physical factors, including the vast land area, a middle latitudinal and eastern coastal location, and mountainous topography (the physiographic provinces and the data sites mentioned in the text are shown in Figure 1).

Climate during the last 150 years

Instrumental records in Guanzi Province of southwestern China (Meteorological Bureau of Guanxi, 1977) indicate that solar activity may be the main factor in determining varia-

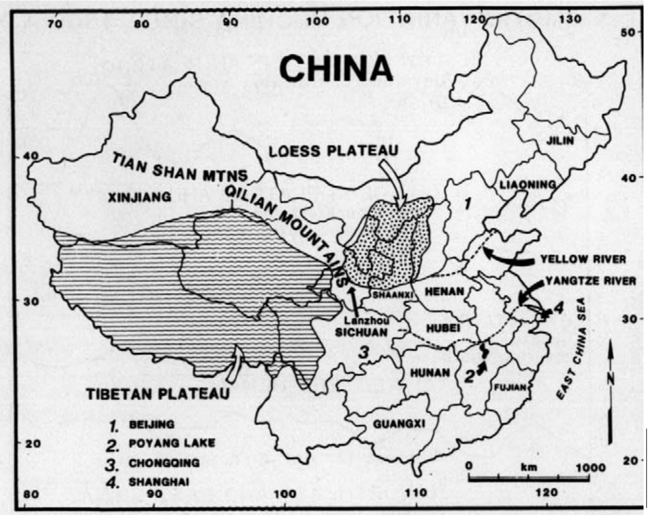

Figure 1 China's physiographic boundaries (Zhao, 1981), provincial divisions and sites mentioned in the text. *Note:* Beijing, Poyang Lake, Chongqing, and Shanghai are numbered 1, 2, 3, and 4, respectively. Yellow River and Yangtze River are marked with dashed lines. Tibetan and loess plateaux are differentiated by shading.

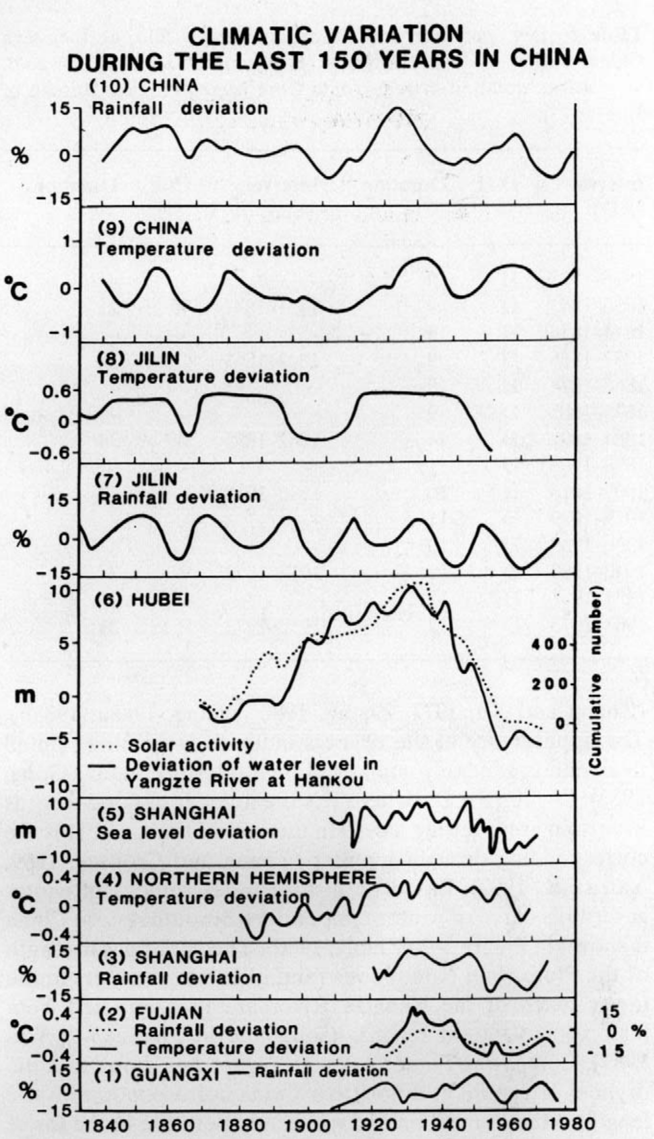

Figure 2 Data on climatic variation during the past 150 years: (1) rainfall deviation from the average (%) in Guangxi (Meteorological Bureau of Guangxi, 1977); (2) temperature deviation from the average (°C) and precipitation deviation from the average (%) in Fujian (Meteorological Bureau of Fujian, 1977); (3) precipitation deviation from the average (%) in Shanghai (Yang and Xie, 1984); (4) temperature deviation (°C) from the present in the northern Hemisphere (Yang and Xie, 1984); (5) sea-level deviation from the present level (m) in Shanghai (Yang and Xie, 1984); (6) solar activity (cumulative number of sun spots) observed in Shanghai and water-level deviation from the present level (m) at Hankou of Hubei Province (Office of Yangtze River, 1977); (7) and (8) precipitation and temperature deviations from the averages in Jilin (Ding, 1977; Meteorological Bureau, 1977); (9) and (10) temperature and precipitation deviations from the present in China (Wang and Zhao, 1979a; 1979b).

tions of temperature and precipitation. Temperature and precipitation values appear to oscillate during the twentieth century, i.e.: 1901–1920, cold and wet; 1921–1940, warm and wet; 1941–1950, warm and dry; and 1951–1970, cold and dry (Figure 2-1). In Fujian Province of southeastern China (Meteorological Bureau of Fujian, 1977), the temperature curve has a trend similar to that of precipitation, but with greater variability (Figure 2-2). The precipitation deviation (variation relative to the mean) in Shanghai (Figure 2-3; Yang and Xie, 1984) is approximately the same as that of Fujian, both being located at the Pacific Coast, but different from that of Guanxi, which is more influenced by the Indian Ocean. According to Yang and Xie (1984) and Office of the Yangtze River (1977), the temperature oscillations of the Northern Hemisphere (Figure 2-4) correspond with the precipitation deviation and the sea-level deviation in Shanghai (Figure 2-5), and to the deviation of water level of the Yangtze River at Hankou of Hubei Province which is in phase with solar activity variations (Figure 2-6).

In Jilin Province of northeastern China, Ding (1977) shows that precipitation deviation has the same periodicity (about 11 years) as solar activity cycles. The research indicates that the periods 1940–1950 and 1962–1973 were the two driest, while 1844–1897 and 1903–1918 were the two wettest of the past 150 years (Figure 2-7). Both the instrumental record and its relationship to tree rings (Meteorologic Bureau of Jilin, 1977) indicate that each temperature cycle (20–23 or 33–34 years) is associated with two or three precipitation cycles with a 9–11 year periodicity (Figure 2-8), and a long warm period consists of two humid and one dry period (Table 1). Overall, the temperature of China appears to be influenced by the position of the Mongolian High (Figure 2-9), whereas the precipitation is closely related to the position of the Southern Pacific High (Figure 2-10). When the strong Mongolian High moves southward and reduces the strength of the Southern Pacific High, the temperature in China is relatively low and so is the precipitation (Wang and Zhao, 1979a; 1979b).

In conclusion, during the last 150 years, warm and humid periods occurred in AD 1840–1850, 1870–1885, 1920–1940, and around 1960; whereas cold and dry periods occurred in 1830–1840, 1860–1870, 1890–1920, 1940–1950, and 1963–1973. Through comparison, it can be seen that major warm and cold events in Jilin, northeastern China, correspond well with major humid and dry events in the Tianshan Mountains of northwestern China (Zhang, 1984; Kang, 1983; 1985); however, there is some time lag (Table 2).

Climate during the last 500 years

Using the historic data for central and northern China, Zhang and Xu (1977) designed a dryness index: number of flood counties minus number of drought counties for a specified time interval. The reconstructed index (Figure 3-1) demonstrates two extremely dry periods around AD 1625 and 1800

Table 1 Dry, wet, cold and warm intervals in Jilin, northeastern China, during the last 150 years (H = humid, D = dry, C = cold, W = warm, duration in years; data from Meteorological Bureau of Jilin, 1977).

Interval (AD)	D/H	Duration	Interval (AD)	C/W	Duration
1826–1835	H	9	–	–	–
1836–1843	D	9	1821–1841	W	21
1844–1856	H	13	–	–	–
1857–1865	D	9	1842–1861	C	20
1866–1874	H	9	–	–	–
1875–1883	D	9	–	–	–
1884–1897	H	14	1862–1895	W	34
1898–1908	D	11	–	–	–
1909–1918	H	10	1896–1918	C	23
1919–1929	D	11	–	–	–
1930–1939	H	10	–	–	–
1940–1950	D	11	1919–1952	W	34
1951–1961	H	11	–	–	–
1962–1973	D	12	1952–1973	C	21

(Zhang and Xu, 1977; Zhang, 1980; Zhang, 1988a; 1988b). The applicability of the dryness index to estimating rainfall deviation is generally supported by a moisture index (Gong, 1983): $I = 2F/(F + D)$, where F is the number of flood records in certain areas during a certain interval of time, and D is the corresponding drought number (Zhang and Crowley, 1989; Yan *et al.*, 1992). Based on historical descriptions of winter severity, a curve of winter temperature in southeastern China is shown in Figure 3–2 (Zhang, 1980). The variations in length of the Plum Rain (continuous rainfall in late summer) in the lower reach of the Yangtze River are reconstructed from historic agricultural records (solid line in Figure 3–2; Wu, 1983). Comparing Figure 3–1 with Figure 3–2 shows that the dryness of central and northern China corresponds with the length of the Plum Rain and winter temperature in the lower reach of the Yangtze River. Trends varied over the 500-year period: 1470–1522 was wet to dry; 1522–1560, dry to wet; 1560–1624 was wet to dry but typified by frequent wet spells; while 1625–1650 was very dry. No significant variation occurred from 1651 to 1724 in the length of the Plum Rain. A dry period extended from 1725 to 1786; a wet period from 1787 to 1851; and from 1852 to 1932, rainfall was generally low. Periods of cooling were 1470–1520, 1620–1720 (particularly 1650–1700), 1840–1890 and after 1945 (Zhang *et al.*, 1974; Climate Research Group of Nanking University, 1977).

Tree rings have been used as an indicator of precipitation in Hunan Province of southern China. The tree-ring data indicate that the periods of high precipitation from 1780 to 1900 in southern China (Figure 3–3; Meteorologic Bureau of Hunan, 1977) corresponded roughly with the dry periods in central and northern China. The deviation of freezing duration in Poyang Lake of Jianxi Province (adjacent to Hunan Province) appears to correspond with both the length of the Plum Rain and winter temperature in southeastern China (Figure 3–4; Meteorological Bureau of Jianxi, 1977).

The best-documented and well-preserved historic records in Beijing, then capital city for several Dynasties, show that there were more floods in the first half and more droughts in the second half of the last 500 years (Figure 3–5; Meteorological Bureau of Beijing, 1977; Wang and Zhao, 1981; 1984; Zhang, 1984; Wang, 1989). The data also indicate that wet periods became shorter (56–24–16 years), and drought periods longer (42–45–54 years). The same studies also show that in eastern and northeastern China the first half of the last 500

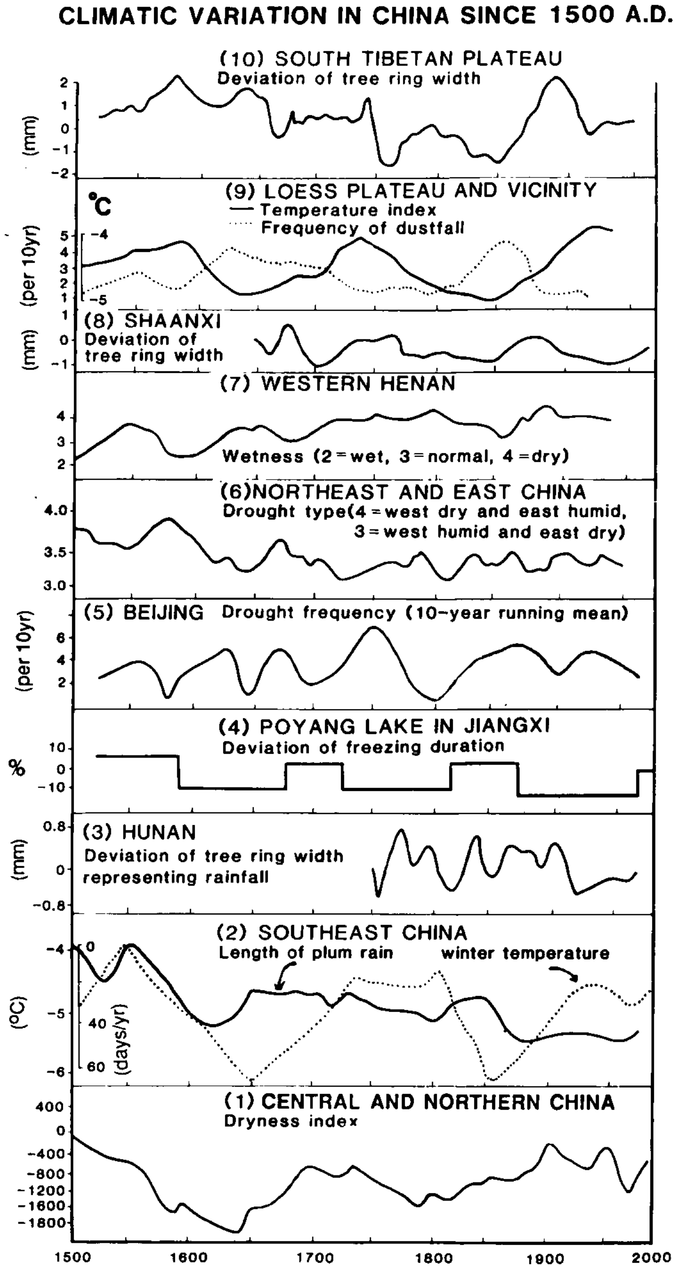

Figure 3 Data on climatic variations during the past 500 years: (1) dryness index (the number of flooding counties minus the number of drought counties in certain areas for a certain period of time) in central and northern China according to historic records (Zhang and Xu, 1977; Zhang, 1980; Zhang, 1988a; 1988b); (2) winter temperature (dashed line) reconstructed from historic descriptions of winter severity (Zhang, 1980) and the length of plum rain according to historic agricultural records (Wu, 1983) in southeastern China; (3) deviation of tree-ring width from the average, representing precipitation deviation (Meteorological Bureau of Hunan, 1977) in Hunan; (4) deviation of freezing duration from the present, Poyang Lake in Jiangxi (Meteorological Bureau of Jianxi, 1977); (5) drought frequency (per decade) in Beijing (Wang and Zhao, 1981; Zhang, 1984; Wang, 1989); (6) drought-type index in eastern and northeastern China (Wang and Zhao, 1984); (7) wetness index in Henan (Wang and Zhao, 1984; Zheng and Feng, 1985); (8) deviation of tree-ring width from the average, representing deviation of precipitation in Shaangxi (Meteorological Bureau of Shaangxi, 1977); (9) estimated frequency of dustfall and temperature in the Loess Plateau (Zhang, 1980; 1984); (10) tree-ring deviation from the average (mm), representing temperature deviation, in the southern Tibet Plateau (Wu and Lin, 1981a; 1981b).

years was characterized by a relatively dry west and humid east; whereas the second half saw a humid west and a dry east (Figure 3–6). Historic records in Henan Province and elsewhere in central China (Wang and Zhao, 1979a; 1979b; 1984; Zheng and Feng, 1985) confirm that climatic conditions in central China were opposite those of the east coast: i.e., the first half was moist and the second half dry (Figure 3–7). Tree rings in the adjacent Shaanxi Province, used as an indicator of precipitation, demonstrate a similar dryness trend as in Henan (Figure 3–8; Meteorological Bureau of Shaanxi, 1977).

Historic dustfall records from China indicate that dustfall primarily occurred during cold periods (Figure 3–9; Zhang, 1980; 1984). For example, 1621–1700 and 1811–1900 were two cold periods, coupled with a high frequency of dustfall (3.7 year/decade), whereas 1511–1620 and 1721–1780 were two warm periods, accompanied by a low frequency of dustfall (2.1 year/decade). To the west, the Tibet Plateau is an ideal place for tree-ring study as temperature is the controlling factor of tree growth at the upper limit of forest while precipitation is the controlling factor at the lower limit. The tree-ring data (Lin and Wu, 1977) show that 1520–1650 and 1916–1950 were two warm and wet periods. The precipitation of the last 200 years was below average from 1750 to 1870, above average from 1870 to 1960, and below again since 1960. The 'Little Ice Age' appears pronounced from 1730 to 1916 in the tree-ring spectrum (Figure 3–10; Wu and Lin, 1981a; 1981b).

In summary, during the last 500 years the climate was predominantly cold or cool and the frequencies of flood and drought increase toward the present (Wang and Wang, 1990). Based upon the historic data, four cycles can be distinguished: 1470–1520, 1650–1720, 1840–1890, and 1945–1960 were relatively cold. All these cold episodes are well recorded by dust-content and oxygen-isotope variations in the ice core of the Dunde Ice Cap, Qilianshan Mountains (Yao *et al.*, 1991). Besides the comparability of temperature changes in Jilin, northeastern China, with precipitation changes in the Tianshan Mountains of northwestern China (Table 2), dryness or moistness in Beijing (eastern China) is comparable with that in the Qilianshan Mountains of northwestern China (Wang and Zhang, 1984) with a time-lag in the northwest and with the exception of a short wet period from 1644 to 1652 (Table 3).

Table 2 Comparison of the temperature in Jilin, northeastern China, with precipitation in the Tianshan Mountains of northwestern China (H = humid, D = dry, C = cold, W = warm, the data from Meteorological Bureau of Jilin, 1977; Zhang, 1984; and Kang, 1983; 1985).

Interval (AD)	C/W	Interval (AD)	D/H
Jilin		Tianshan	
1807–1841	W	–	–
1842–1861	C	1841–1854	H
1862–1895	W	1855–1868	D
1896–1918	C	1869–1877	H
1919–1952	W	1878–1904	D
1952–1980	C	1905–1941	H
–	–	1942–1980	D

Table 3 Comparison of the dry and wet intervals in Beijing, eastern China, with those in the Qilian Mountains of western China during the last 500 years (H = humid, D = dry, the data from Meteorological Bureau of Beijing, 1977; Wang and Zhao, 1984; and Wang and Zhang, 1984).

Interval (AD)	D/H	Interval (AD)	D/H
Beijing		Qilian Mountains	
1440–1482	H	1420–1460	H
1483–1535	D	1461–1560	D
1536–1580	H	1561–1630	H
1581–1643	D	–	–
1644–1657	H	–	–
1658–1694	D	1631–1687	D
1695–1724	H	1688–1715	H
1725–1769	D	1716–1770	D
1770–1825	H	1771–1845	H
1826–1870	D	1846–1867	D
1871–1894	H	1868–1882	H
1895–1948	D	1883–1910	D
1949–1964	H	1911–1922	H
1965–1980	D	1922–1980	D

Climate during the last 10 000 years

Based upon historic records (i.e., phenology, agricultural documentation, diaries of officials and family genealogy, etc.), Chu (1973) reconstructed a temperature curve for the past 5000 years (Figure 4–1). By studying historic records of elephant migration in central and southern China, snow cover duration and extent in eastern China, the duration of the plum rain and the frequency of typhoons in southeastern China, Chu's temperature curve was independently confirmed by Zhu (1977). Four temperature cycles were recognized during the past 5000 years (Figure 4–2):

1st warm: 5000–3000 BP	1st cold: 3000–2800 BP
2nd warm: 2700–2000 BP	2nd cold: 2000–1400 BP
3rd warm: 1400–1000 BP	3rd cold: 1000–800 BP
4th warm: 800–700 BP	4th cold: 600–100 BP

Based on pollen assemblages from southeastern China (Wu, 1983; Xu, 1983; Xu and Shen, 1990; Liu *et al.*, 1992), the 5000-year temperature curve of Chu (1973) has been extended to 10 000 BP in Figure 4–1 (but note that 8000–10 000 BP is not shown on Figure 4–1 due to a limited space). This extension is generally supported by pollen assemblages from eastern China (Kong, 1980; Zhao, 1982; Li, 1985; Kong and Du, 1990) and geological evidence from the deltaic sediments of the Yangtze River (Yang and Xie, 1984). The extended temperature curve indicates that the period between 10 000 and 9000 BP was one of increasing temperature and that 9000–3000 BP was the 'Optimal Period' of the past 10 000 years. The so-called 'Optimal Period' was about 2–3°C warmer than the average from AD 1900–70. Two minor cold intervals around 7300 and 5700 BP divided the 'Optimal Period' into three warm subperiods: 9000–7800, 7500–5800 and 5300–3000 BP, with a slight cool interval around 4500 BP. It is interesting to note that the four periods of brilliant Chinese Culture (7800–7300, around 6000, 5900–5600 and 5500–4900 BP) were within the 'Optimal Period' (Feng, 1985; Editing Group of Chinese Historic Mapping, 1974).

At Chongqing of Sichuan Province, Three Gorges of the Yangtze River, many monuments were established about 800 years ago to record extreme water levels. The water-level

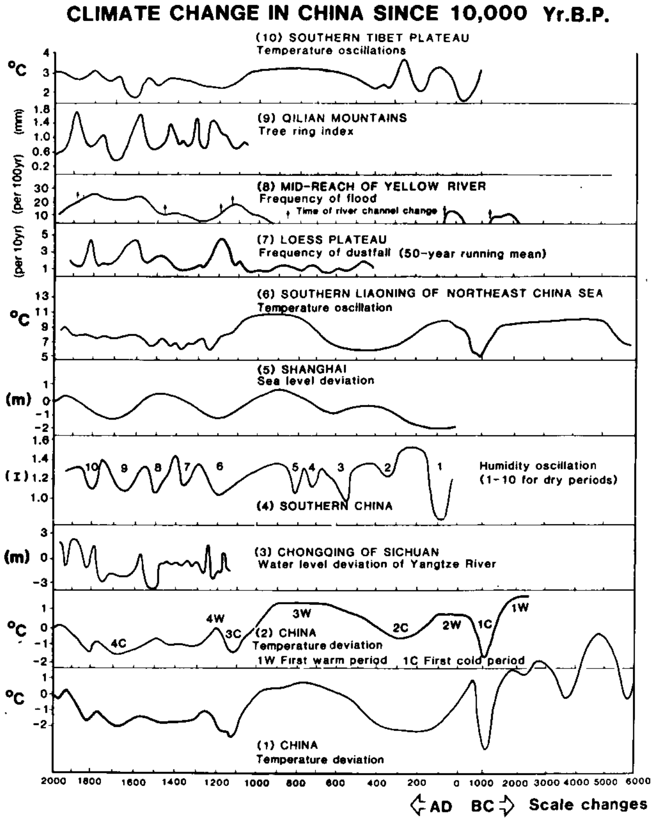

Figure 4 Data on climatic variation during the past 10 000 years: (1) temperature deviation from the present in China, based on historic records (Chu, 1973), and archaeological (Wu, 1983) and geological evidence (Xu, 1983; Xu and Shen, 1990); (2) independently reconstructed temperature deviation from the present in China (Zhu, 1977); (3) water-level deviation from the average at Chongqing (Office of Yangtze River, 1977); (4) humidity index (I) in southern China, $I = 2F/(F+D)$ where F is the number of flood records in certain areas for a certain period of time and D is the corresponding drought records (Zheng and Feng, 1975, 1985); (5) sea-level deviation from the present (m) in Shanghai (Yang and Xie, 1984; Yang, 1979); (6) temperature oscillation in southern Liaoning, based on geological evidence (Guiyang Institute of Geochemistry, 1977; Qu, 1981); (7) frequency of dustfall (per decade) on the Loess Plateau (Zhang, 1984); (8) frequency of flood (per century) in the middle reach of the Yellow River (Feng, 1987); (9) tree-ring width (mm) in Qilianshan Mountains (Wang and Zhang, 1984); (10) temperature oscillation estimated from tree-ring data (Wu and Lin, 1981a; 1981b).

extremes were also traced on Buddhist statues in the river walls which were sculptured at different times. Archaeological studies of these records confirm that the water level at the middle reach of the Yangtze River has fluctuated more since the seventeenth century. The driest period occurred in the sixteenth century. The water level was more-or-less stable from the sixteenth to thirteenth centuries and oscillated dramatically around twelfth century (Figure 4–3; Office of the Yangtze River, 1977). The curve of discharge at the middle reach is similar to that of the humidity or moisture index, $I = 2F/(F+D)$, exhibited by the lower reach (Zheng and Feng, 1977; 1985). Zheng and Feng identified 10 dry periods during the past 2000 years in southern China. The longest wet spell occurred in AD 811–1050, while the longest dry spell appeared in AD 1051–1270 (Figure 4–4). They also showed that the frequencies of drought and flood increase dramatically toward the present, similar to the Yellow River area. The index of humidity has increased during dry spells, while during the wet spells it has decreased toward the present. Sea-level deviations in Shanghai during the last 2000 years have been archaeologically reconstructed based on buried artifacts in beaches (Yang, 1979). The reconstructed sea-level deviations (Figure 4–5) correspond generally to the humidity oscillations, i.e., major dry periods (1st, 3rd, 6th, 9th) mirror lower sea levels (Yang and Xie, 1984).

Studies on pollen assemblages (Qu, 1981), sedimentological properties (Guiyan Institute of Geochemistry, 1977), and the contraction and expansion of permafrost (Qu, 1981; Cui and Xie, 1985) in Liaoning Province of northeastern China indicate that the period of 10 000–8500 BP was one of increasing temperature, while 8500–3500 BP was climatically the most favorable period with annual temperature of 3–5°C higher than the average of AD 1900–1970. Two other warm periods occurred at AD 0–200 and AD 700 to 1000. Changes in the southern latitudinal limit of permafrost in northeastern China have been approximately in phase with changes in the lower altitudinal limit of permafrost and in the terminal positions of glaciers on the Tibet Plateau (Li and Feng, 1984; Wang and Zhang, 1985; Wang, 1985; Pan and Xu, 1989; Zhang, 1991), and in permafrost activity on the Ordos Plateau of northern China (Dong, 1985). The reconstructed Holocene temperature can also be related to changes in magnetic susceptibility of Holocene loess, which reflects dust influx to the Loess Plateau (An *et al.*, 1990; Li *et al.*, 1990; Zhou *et al.*, 1991).

On the Loess Plateau of central China, there were five periods of frequent dustfall since AD 300: AD 1060–1090, 1160–1270, 1470–1560, 1610–1700, and 1820–1890 (Zhang, 1984). Each cycle is approximately 90 years in length (Figure 4–7). Comparing Figures 4–6 and 4–7 suggests that the cold spell of AD 1000–1200 corresponded with the high frequency of dustfall of 1100–1300 with a 100-year delay, and the cold spell of 1400–1900 with frequent dustfall of the same time. More interestingly, the historically documented frequency of flooding and channel migration in the Yellow River (Figure 4–8; Feng, 1987) roughly reflect the temperature oscillations in China. The first channel migration of the Yellow River occurred before 3000 BP, and there was almost no flooding from 3000 to 2800 BP. More flooding and the second channel migration occurred from 2700 to 2000 BP, and no flooding was recorded from AD 0–800. A low frequency of floods occurred in the cold spell of AD 1000–1300 and many more floods were recorded after AD 1400. Disastrous famine events due to crop failure in Lanzhou (Gansu Province), which have been carefully documented by the governments at all times in this agriculturally vulnerable region, were caused by persistent droughts during cold periods (Feng, 1987). In the adjacent Qilianshan Mountains, east of the Tibet Plateau, where tree rings are temperature sensitive, the tree-ring index (i.e., width of the ring) exhibits two distinct cold periods: AD 1060–1154, relating to the old episode of eleventh and twelfth centuries, and around the seventeenth century, corresponding with the peak of the 'Little Ice Age' (Figure 4–9; Wang and Zhang, 1984).

In the Tibet Plateau, tree rings have recorded the variations in temperature of the past 3000 years, which are also reflected by glacial advance and retreat (Lin and Wu, 1975; Wu and Lin, 1981a; Li and Feng, 1984). The glaciers in the southern and eastern Tibet Plateau advanced around 2800, 2000, 1900, 1500 BP, and in the seventeenth–nineteenth centuries, and retreated from the mid-sixth to late-twelfth centuries. The limited data suggest that the warm spells may have been longer and the cold spells shorter on the plateau than in other parts of China. On the basis of permafrost evidence in the northern Tibet Plateau, the following sequences are reconstructed (Wang and Zhang, 1985; Wang, 1985; Pan and Xu, 1989): increasing temperature (10 000–8500 BP), warm

(8000–3500 BP), cold (3500–2000 BP), increasing temperature (2000–500 BP), and the modern 'Little Ice Age' (AD 1400–1900). Lake contraction and expansion in the southern Tibet Plateau (Gasse *et al.*, 1991) and in the intermontane basins east of the Tibet Plateau (Chen and Bowler, 1985; Chen, 1990) record dryness in western China, which is coincident with the reconstructed temperature, suggesting that cold dry and warm moist have been usual combinations in western China.

Summary

Geological, tree-ring and archaeological data, and an almost 5000-year historic record supplement one another to provide a detailed picture of climate change in China over the past 10 000 years. The last 10 000 years were characterized by climatic oscillations with varying periodicities. 10 000–9000 BP was a period of increasing temperature. 9000–3000 BP was the 'Optimal Period' (moist and warm) within which there were two major cool episodes around 7300 and 5700 BP, and a minor cool episode around 4500 BP. After the 'Optimal Period', i.e., during the Neoglaciation, three warm episodes occurred about 2700–2000, 1400–1000 and 800–700 BP. The last 1000 years was typified by warming in the first half and cooling in the second half. During the second half, AD 1520–1650, 1720–1840, and 1890–1945 were warm intervals. The warm and wet regimes were characterized by denser and higher vegetation and fewer occurrences of less intense dustfall on the Loess Plateau of northern China, more floods in the Yellow River and Yangtze River Valleys, a higher growth rate of tree in northern China, and a shorter duration of lake freezing in southern China. Over the long term, climate in China has changed synchronously from the east to the west and from the south to the north. But, it has changed asynchronously over the shorter term. For example, during the last 500 years, the first half was dry in the west and wet in the east but the second half was marked by drying in the east and increasing humidity in the west.

Acknowledgements

This research was financially supported by the Ohio Board of Regent Research Challenge Program. We express our appreciation to Dr Li Jijun and Dr Kang Jiancheng who helped us locate some data in China; also to Dr W.C. Johnson and Dr G. Kukla for reviewing the earlier draft. We especially thank Dr W.H. Berger for his encouragement and constructive comments.

References

An, Z., Wu, X., Lu, C., Zhang, D., Su, X. and **Dong, G.** 1990: Environmental changes in China for the recent 20 000 years. In Liu, T., editor, *Loess, quaternary geology and global change*, Volume II. Beijing: Science Press, 1–26.

Chen, K. 1990: Environmental changes in the Tibet Plateau during the past 40,000 years *Quaternary Studies* 1, 21–31.

Chen, K. and **Bowler, J.M.** 1985: Salty lacustrine deposits and their paleoclimates in Chagar Salty Lake, Qaidam Basin. *Scientia Sinica* B5, 464–73.

Chu, K. 1973: A preliminary study on the climatic fluctuation during the last 5000 years in China (in English). *Scientia Sinica* 16, 226–56.

Climate Research Group of Nanking University 1977: Droughts and floods in China since 500 years BP. In *Proceeding of prediction of long term climatic change*, Beijing: Science Press, 53–58.

Cui, Z. and **Xie, Y.** 1985: Periglacial environments in northern China. *Glaciology and Geocryology* 6(2), 115–23.

Ding, S. 1977: The test for the periodicity of rainfall in 1960s in Jilin. In *Proceedings of prediction of long term climatic change*, Beijing: Science Press, 123–25.

Dong, G. 1985: Periglacial environment since the last glaciation in the Ordos Plateaus of northern China. *Geographic Research* 4(1), 1–12.

Editing Group of Chinese Historic Mapping 1974: Chinese historic Maps. Beijing: Shangwu Press.

Feng, S. 1985: Origin of China's agriculture on the basis of Dadiwan Relics, Qinan, Gansu. *Acta Geographica Sinica* 40(3), 123–33.

Feng, Z.D. 1987: The climate of China during the last 10,000 years. *Open-file report of BPRC of Ohio State University*. **Notes:** the histories of flooding of the Yellow River and drought in Gansu of northwestern China are mainly based on the data from Zheng Zhaojing (*Water conservation of China*, Taiwan: Zhongzheng Press, 1966), Feng Shengwu (*Historic records of natural calamities in Hexi Corridor and Qaidam Basin*, Gansu Publishing House, 1980), Zhang Liyuan (*Historic important events of Lanzhou*, Gansu Publishing House, 1986), and Zhao Shiying (*Historic important events of Gansu*, Gansu Publishing House, 1984).

Gasse, F., Arnold, M., Fontes, J.C., Fort, M., Gibert, E., Huc, A., Li, B., Li, Y., Liu, Q., Melieres, F., Campo, E.V., Wang, F. and **Zhang, Q.** 1991: A 13,000 year climate record from western Tibet Plateau. *Nature* 353, 742–45.

Gong, G. 1983: The methodology of studying climatic fluctuations in historic times. *Climate of China* 32–44. Shanghai: Science and Technology Press.

Guiyan Institute of Geochemistry 1977: Changes of natural environment in the southern part of Liaoning during the past 10,000 years (in English). *Scientia Sinica* 21(6), 523–34.

Kang, X. 1983: Tree rings and climatic change in Bogoda Mount, Tianshan Mountains. *Glaciology and Geocryology* 5(3), 153–69.

—— 1985: Climatic analysis of tree ring in Wurumuqi River Basin, Tianshan Mountains. *Glaciology and Geocryology* 7(2), 172–76.

Kong, Z. 1980: Vegetational evolution in Beijing since 30,000 yr BP. *Botany of China* 22, 330–38.

Kong, Z. and **Du, L.** 1990: Vegetation and climate during the Holocene 'Optimal Period' in certain areas of China. *Oceanic and Quaternary Geology* 10(1), 99–102.

Li, J. and **Feng, Z.D.** 1984: Quaternary glaciations in Hongduan Mountains. In Proceedings of Mountain Glaciers and Glaciations. *Journal of Lanzhou University* 6, 61–72.

Li, J., Zhu, J. and **Kang, J.** 1990: Climatic comparison between Lanzhou Loess and Vostok ice core of Antarctica. *Scientia Sinica* B6, 656–62.

Li, Y. 1985: Microfauna and its paleogeographic meanings in Tianjing Plain. *Acta Geographica Sinica* 40(2), 160–67.

Lin, Z. and **Wu, X.** 1975: Climatic change in southern Tibet Plateau. *Meteorology* 20(9), 31–35.

Lin, Z. and **Wu, X.** 1977: Approaching to historic climate of the Tibet Plateau. In *Proceedings of prediction of long term climate change*, Beijing: Science Press, 23–28.

Liu, K., Sun, S. and **Jiang, X.** 1992: Environmental change in the Yangtze River Delta since 12,000 yr BP. *Quaternary Research* 38, 32–45.

Meteorological Bureau of Beijing 1977: Analysis of drought and flood during the past 500 years in Beijing. In *Proceedings of prediction of long term climate change*, Beijing: Science Press, 126–28.

Meteorological Bureau of Fujian 1977: A preliminary analysis of Fujian climate since this century. In *Proceedings of prediction of long term climate change*, Beijing: Science Press, 10–15.

Meteorological Bureau of Guanxi 1977: Climatic tendency of Guanxi in this century. In *Proceedings of prediction of long term climate change*, Beijing: Science Press, 132–34.

Meteorological Bureau of Hunan 1977: The fluctuations of humidity in Hunan on the basis of tree rings. In *Proceedings of predicition of long term climate change*, Beijing: Science Press, 59–63.

Meteorological Bureau of Jiangxi 1977: Winter severity and freezing duration of Poyang Lake, Jiangxi, since 1000 year BP. In *Proceedings* *of prediction of long term climate change*, Beijing: Science Press, 16–17.

Meteorological Bureau of Jilin 1977: The predicition of long term climate based on tree rings in Jilin. In *Proceedings of prediction of long term climate change*, Beijing: Science Press, 123–25.

Meteorological Bureau of Shaanxi 1977: Climate change and tree rings in Shaanxi. In *Proceedings of prediction of long term climate change*, Beijing: Science Press, 72–76.

Office of the Yangtze River 1977: Records of water level of Yangtze River. In Chongqing Museum of Natural History, editor, *Proccedings of archaeological studies on volcanoes, deserts, and hydrology of the Yangtze River*, Beijing: Archaeological Press, 45–51.

Pan, B. and **Xu, S.** 1989: Environmental change during the late Quaternary in eastern Tibet Plateau. *Kexue Tongbao* 34(7), 534–36.

Qu, S. 1981: Environmental changes since the last glaciation in northeastern China. *Acta Geographica Sinica* 36(3), 315–27.

Wang, F. 1985: Climate and the future trend in the Tibet plateau. In *Proccedings of quaternary glaciation and geology*, Beijing: Geology Press, 153–61.

Wang, S. and **Wang, Y.** 1990: Little ice age in China. *Kexue Tongbao* 35(10), 769–72.

Wang, S. and **Zhang, W.** 1985: Permafrost evolution in Qinshui River of the Tibet Plateau since the late Quaternary. *Journal of Glaciology and Geocryology* 7(1), 15–23.

Wang, S. and **Zhao, Z.** 1979a: Periodicity of drought and flood in China. *Meteorology* 5(1), 12–14.

—— 1979b: The 36-year wetness oscillation in China and its mechanism. *Acta Meteorology Sinica* 37, 233–38.

—— 1981: Drought and flood in China, 1470–1979. In T.M.L. Wigley *et al.*, editors, *Climate and history*, Cambridge: Cambridge University Press, 271–88.

—— 1984: Drought and Flood in China from 1470 to 1977. In *Proceedings of climatic change in China* (in English), Beijing: Science Press, 117–30.

Wang, S. 1989: EI Nino events from 1470–1988. *Meteorology* 30(15), 15–20.

Wang, Y. and **Zhang, X.** 1984: The relationship between tree ring and climate change since 1000 years BP in Qilian Mountains. *Kexue Tongbao* 28(2), 1647–52.

Wu, W. 1983: Holocene paleogeography in Hanzhou Bay inferred from cultural relics of Neolithic Time. *Acta Geographica Sinica* 38(2), 321–27.

Wu, X. and **Lin, Z.** 1981a: Climate change of the Tibet Plateau since historic time. In *Proceedings of geologic and ecological studies of Tibet Plateau* (in English), Beijing: Science Press, 1578–85.

—— 1981b: Some characteristics of climatic changes during the historic times in Qinghai-Xizang Plateau. *Acta Meteorology Sinica* 39, 90–96.

Wu, X. 1983: The climate fluctuations of Plum Rain in China during the past 500 years (in English). *Scientia Sinica* 28(11), 211–15.

Xu, Q. 1983: Evolution of vegetation and climate in Zhengjiang near Nanking since 15,000 years BP. *Acta Geographica Sinica* 39(3), 62–67.

Xu, Q. and **Sheng, Z.** 1990: Environments of China during the Holocene. Guizhou Publishing House.

Yan, Z., Ye, D. and **Wang, C.** 1992: Climatic jumps in flood/drought historic chronology of central China (in English). *Climate Dynamics* 6, 153–60.

Yang, H. and **Xie, Z.** 1984: The processes and tendencies of sea level and climate changes (in English). *Acta Geographica Sinica* 39(1), 156–62.

Yang, H. 1979: Climate change during the Quaternary. *Glaciology and Geocryology* 1(1), 25–34.

Yao, T., Xie, Z., Wu, X. and **Thompson, L.G.** 1990: Little Ice Age as recorded in Dunde Ice Cap of Qilianshan Mountains. *Scientia Sinica* B11, 1196–201.

Zhang, D. 1980: Some characteristics of winter temperature variation in southern China during the past 500 years (in English). *Kexue Tongbao* 25(6), 270–72.

—— 1984: Synoptic-climatic studies of dustfall in China since historic time (in English). *Scientia Sinica* B27(3), 277–88.

Zhang, J. and **Crowley, T.J.** 1989: Historic climate records in China and reconstruction of past climate (in English). *Journal of Climate* 2(8), 833–49.

Zhang, J. 1988a: The methods of reconstruction of dryness/wetness series in China for the last 500 years and its reliability. In Zhang, J., editor, *The reconstruction of climate in China for historic times*, Beijing: Science Press, 18–31.

—— 1988b: Drought and flood fluctuation and its relation with general atmospheric circulation. In Zhang, J., editor, *The reconstruction of climate in China for historic times*, Beijing: Science Press, 66–91.

Zhang, J., Zhu, M. and **Zhang, X.** 1974: Climate changes in China. *Kexue Tongbao* 19(4), 121–123.

Zhang, L., editor, 1991: *New advances of research in Quaternary mountain glaciations of western China*. Beijing: Science Press.

Zhang, X. and **Xu, R.** 1977: The relationship between rainfall deviation and solar activity and the trend of future climate. In *Proccedings of prediction of long term climate change*, Beijing: Science Press, 92–99.

Zhang, X. 1980: The analysis of index of dryness since the past 500 years in China. In *Proceedings of climatic fluctuation*, Beijing: Science Press, 41–48.

—— 1984: Glacial advances and climate changes in Tianshan Mountains during the past 250 years. *Journal of Glaciology and Geocryology* 6(4), 1–12.

Zhao, S. 1981: *Physical geography of China*. New York: John Wiley & Sons.

Zhao, X. 1982: Paleogeographic evolution of Beijing Plain. *Scientia Sinica* 27(11), 1189–96.

Zheng, S. and **Feng, L.** 1985: Historic evidence of extra-instability during cold period in China (in English). *Scientia Sinica* 28, 1038–44.

Zheng, S., Zhang, F. and **Gong, G.** 1977: The change of humidity in southeastern China since 2000 years BP. In *Proceedings of prediction of long term climate change,* Beijing: Science Press, 29–35.

Zhou, S., Chen, F., Pan, B., Li, J. and **Derbyshire, E.** 1991: Environmental change during the Holocene in western China on a millennial timescale (in English). *The Holocene* 2, 151–56.

Zhu, M. 1977: The climatic fluctuations at different time scales in China. In *Proceedings of Prediction of long term climatic change*, Beijing: Science Press, 36–44.