The Holocene 13,6 (2003) pp. 933–940

Winter half-year temperature reconstruction for the middle and lower reaches of the Yellow River and Yangtze River, China, during the past 2000 years

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Received 2 January 2002; revised manuscript accepted 5 October 2002

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REPORT

Abstract: Phenological cold/warm events recorded in Chinese historical documents are used to reconstruct, at 10–30 years' resolution, winter half-year (October to April) temperatures for the past 2000 years in the central region of eastern China. Because of the uneven spatial and temporal distribution of the phenological records, the reconstruction of the regional mean temperature involves two steps: reconstruction for individual sites within the region and calculation of the regional mean. For a single site, the reconstruction involves: identifying the difference in dates in phenological events for both historical and modern records; establishing the conversion function between the date difference and temperature change from the modern records; and converting the historical records into temperature variation. The spatial representativeness of the individual sites is studied by examining the correlation between individual sites and regional mean temperature from modern instrumental data. The correlation is then used as the basis for constructing the regional mean winter half-year temperature for the past 2000 years. From the beginning of the Christian era, climate became cooler at a rate of 0.17°C per century, and around the AD 490s temperature reached about 1°C lower than that of the present (the 1951–80 mean). Then, abruptly, temperature entered a warm epoch from the AD 570s to 1310s with a warming trend of 0.04°C per century; the peak warming was about 0.3–0.6°C higher than present for 30-year periods, but over 0.9°C warmer on a 10-year basis. After the AD 1310s, temperature decreased rapidly at a rate of 0.10°C per century; the mean temperatures of the four cold troughs were 0.6–0.9°C lower than the present, with the coldest value 1.1°C lower. Temperature has been rising rapidly during the twentieth century, especially for the period 1981–99, and the mean temperature is now 0.5°C higher than for 1951–80. The most interesting aspect over the past 2000 years has been the rapid transitions between cold and warm periods.

Key words: Historical climatology, phenology, temperature variations, winter temperatures, late Holocene, China.

Introduction

Climatic change in the past 2000 years is one of the two highlights for PAGES (Eddy, 1992) and, within this timespan, monsoon Asia has been recognized as the region where climatic change records can potentially be extracted from a variety of sources (Bradley, 1993; NSFC, 1998), in particular historical documents (Zhang, 1988; Wang and Zhang, 1988; Zhang and Crowley, 1989). Chu (1973) was the first to use a variety of sources to reconstruct temperature variation in China for the past 5000 years. Since then, many studies have been conducted using a variety of data sources and methodologies to reconstruct 'cold-warm' indices of tempera-

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10.1191/0959683603hl680rr

ture fluctuation in China (Zhang and Gong, 1979; Zhang, 1980; 1993; Wang and Wang, 1990; 1991; Zheng and Zheng, 1993; Wu and Yin, 1991; Wang *et al.*, 1992; Zhou *et al.*, 1994; Gong *et al.*, 1983; Man and Zhang, 1990; 1993). However, most of these studies were limited to the past 1000 years with a majority within the last 500 years.

At the Institute of Geographic Sciences and Natural Resources Research (IGSNRR), Chinese Academy of Sciences (CAS), large amounts of phenological records of cold/warm events, extracted from historical documents spanning over 2000 years, are archived (Zhang *et al.*, 2002; Chu and Wan, 1973). These have been used in a variety of ways to reconstruct temperature changes (Zhang and Gong, 1979; Zhang, 1980; 1993; Wang and Wang, 1990; 1991; Zheng and Zheng, 1993; Wu and Yin, 1991; Wang *et al.*, 1992; Zhou *et al.*, 1994; Gong *et al.*, 1983; Man and Zhang, 1990; 1993; Zhang *et al.*, 2002; Man, 1995). These records can be grouped into two categories.

The first category is 'natural evidence', which provides information about temperature directly. The information includes: phenology of plants, including some crops; the date of the first and last frost and snow; the duration of frost and snow; and the duration of river, lake and sea freeze-up and thaw dates; the distribution and its northern boundary of subtropic crops (e.g., citrus) and economic crops (e.g., tea, bamboo); the spatial-temporal distribution of farming and farming systems (e.g., sowing time, harvest time, the distribution of double harvest rice). The following are a few examples.

> *Prunus mume* were blooming in the 1st lunar month in the North Song Dynasty (960–1126) in Luoyang.[1]
>
> Around 1270s, the 15th day of the 2nd lunar month was the Flowers Festival. At Bao's Garden in Hangzhou, the *Prunus davidiana* Franch blossomed so densely as brocades.[2]
>
> In the 11th lunar month of the 2nd year in Guangqi Reign in Tang Dynasty (886), Huainan was continuingly cloudy with rains and snows till to the 2nd lunar month of the next year.[3]
>
> In the 2nd year in Dazhongxiangfu Reign in the North Song Dynasty (1009), Jingshi (the capital city) was warm and without rivers freezing.[4]
>
> In winter of the 2nd year in Shaoxing Reign in the South Song Dynasty (1132), there was severe cold suddenly, the Taihu Lake was frozen, and the rice boats were delayed. Numerous mountain villagers were starved.[5]
>
> Around 1250s, *Citrus* grew in Xichuan, Tang, and Deng counties, *Citrus sinensis* grew in Huaizhou county. But they did not appear in the north of this region mentioned above.[6]
>
> In the North Song Dynasty (960–1126), Lichee grew in the prefectures of Quan, Fu, Zhang, Jia, Shu, Fu, Xinghua, Guangdong and Guangxi.[7]

The second category is the 'impact evidence', specifically the effect on 'man and society' associated with the cold/warm events. The evidence can be used to extract information about changes in temperature through comparison with other evidence at different times (e.g., the feeling of 'rather cold' and 'warm winter'). A typical example is:

> In the 8th lunar month (10/9–9/10), 17, Wang Mang went to the southern suburb in person to build a large DOU (one kind of containers in ancient China). In the day of building DOU, it was so frosty that many officials and horses were frozen to death.[8]

Note that both categories usually coexisted in the historical documents, for instance:

> In the 12th lunar month of the 1st year in Tianxi Reign in North Song Dynasty (1017), Jingshi (the capital city) suffered from heavy snows and the weather was bitter cold, some people were frozen to death with dead bodies exposed on roadsides.[9]

The records of cold/warm events are scarce before the Tang Dynasty (AD 618–907), but become increasingly more abundant afterwards, particularly since the sixteenth century. The phenological data (the first category) are the major sources before the Tang Dynasty, while data of the second category became available afterwards. The historical weather records emerged during the later Qing Dynasty (AD 1644–1911). Geographically, the records are mostly concentrated in the regions east of 105°E within the latitudinal zones of 25–40°N (referred to as the central region of eastern China). The records are particularly abundant in the middle and lower reaches of the Yellow River and the Yangtze River (Figure 1).

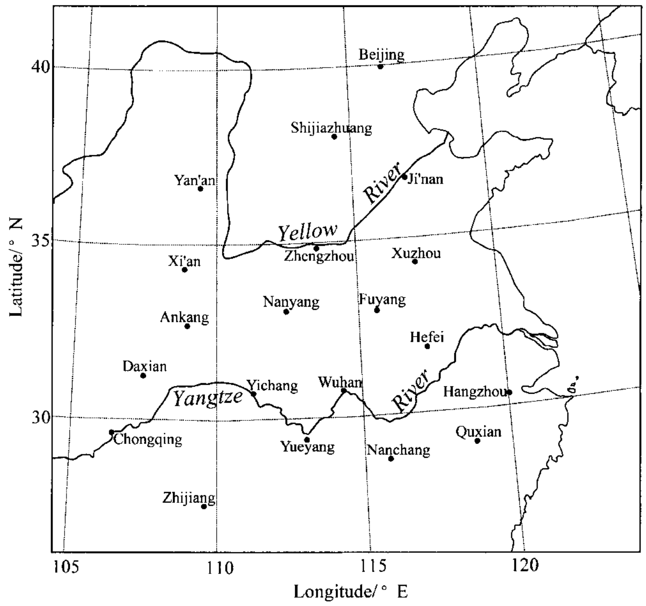

Figure 1 The research domain and the stations for instrumental data analysis.

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[1] From *Henan Shaoshi Wenjianqianlu (A personal note by Shao Bowen in North Song Dynasty)*, Vol. 17.

[2] From *Menglianglu (A personal note by Wu Zimu in the end of South Song Dynasty)*, Vol. 1.

[3] From *Xintang Shu (History of the New-Tang Dynasty), Wu-Xing-Zhi (The Records of Five Elements)*, Vol. 3.

[4] From *Songshi (History of the Song Dynasty), Wu-Xing-Zhi (The Records of Five Elements)*.

[5] From *Jileipian (A personal note by Zhuang Chuo in Song Dynasty)*, Vol. 2.

[6] From Nongsang Jiyao (A guide book for agriculture and mulberry planting), Vol. 5.

[7] From *Tujing Bencao (A guide book for Plants in China by Su Song in North Song)*, Vol. 23.

[8] From *Hanshu (History of the Han Dynasty)*.

[9] From *Songshi (History of the Song Dynasty), Wu-Xing-Zhi (The Records of Five Elements)*.

Data

For winter half-year temperature reconstruction for the past 2000 years, we used primarily the 200 different phenological records of phenomena and crop distribution extracted from historical documents (Man, 1990; Gong and Chen, 1980; Wen and Wen, 1996; Sheng, 1990; Man, 2004). In addition, quantitative temperature reconstruction is also possible by first developing a transfer function between temperature and certain weather/climate events (such as snowing days in winter) from modern meteorological recordings and then applying it to similar weather/climate events recorded in the historical document (Wang *et al.*, 1992; Zhou *et al.*, 1994; Gong *et al.*, 1983). Therefore, in the present study, we also used winter snow-days in the historical documents to supplement the temperature reconstruction from phenological data. However, the method of developing transfer function requires long and continuous records, of which data exist only for limited regions in China for the past 200–300 years. For example, the temperature of Hefei from 1736 to 1980 has been reconstructed by using local winter snow-days extracted from archives during the Qing Dynasty together with the instrumental observations of Nanjing (Zhou *et al.*, 1994). Note that instrumental data are used for the period 1951–99 in the 2000-year temperature time series reported in the present study.

Temperature quantification of a single site

The temperature reconstruction of the winter half-year (October to April) using phenological records and winter snow-days involves two aspects: temperature quantification of the single site and its spatial representativeness.

Phenological records

The relationship between phenological records and temperature is one of the core problems for phenology research (Chu and Wan, 1973). The phenological phenomena are mainly controlled by environmental factors (e.g., temperature, sunshine length, water conditions, soil quality) and to a much lesser extent by inner factors of the organism (e.g., genetic regulation, plant hormones). However, temperature is recognized to be the dominant factor determining phenological 'phase' because the initiation of each development period for plants requires a certain critical temperature and accumulated temperature (Zhang, 1985).

With the compilation of phenological records, the orders of geographical distribution and migration of phenological changes in China were disclosed in the 1980s, and related parameters were calculated using the majority of observed phenological records in China (Gong and Jian, 1983). Table 1 shows that there exists obvious seasonal variation for the geographical distribution of the phenological dates, and that the appearance date of each kind of phenological phenomena reduces gradually with latitude change ranging from the sprouting date of *Prunus persica* Stokes in early spring to the beginning date of flowering of *Juglans regia* L. in late summer.

Based on the large amounts of phenological statistics, the variation of plant phenological date with latitudes and seasons in China can be well synthesized in the following equation:

$$Y = 9.14–2.18\ X–0.569\ X^2 + 0.460\ X^3 - 0.094\ X^4 + 0.0077X^5 - 0.000219X^6 \qquad (1)$$

where Y is the difference in phenological date for every degree of latitude, X is the individual month (e.g., 1 for January) and the correlation coefficient is 0.98. For example, the difference of 1° latitude can result in a difference of 4–5 days for the phenological date of most plants in February and of 3.5 days in spring on average. The analysis of instrumental monthly mean temperature averages indicates a zonal orientation; for example, a 1° difference in latitude (at the same altitude) implies a 0.92°C difference for February and 0.43°C for spring in temperature in the Plains region around 115°E of eastern China (Gong and Jian, 1983). Therefore, a 4–5-day difference of phenological date in February would mean a 0.92°C difference of temperature in February for this particular region, and an average 3.5-day difference of phenological date in spring means a 0.43°C difference of mean temperature in spring. Therefore, it is reasonable to infer the temperature variation between past and present by calculating the differences of phenological date and location shift (especially the latitudinal migration) between the past and present for the same species. For example, the averaged spring phenological date during the AD 510s–530s was one week later than that of 1951–80 in the middle of the North China Plain (i.e., around the station of Shijiazhuang), which implies that the spring mean temperature during the AD 510s–530s was 0.86°C lower than that of 1951–80.

Winter snow-days

As mentioned above, the AD 1736–1980 Hefei temperature was reconstructed by Zhou *et al.* (1994) using the local winter snow-days. Located in the lower reaches of the Yangtze River, Hefei has abundant moisture supply and snow is mainly controlled by the outbreaks of cold air and cold-front activity. Statistics from the meteorological data indicate that the number of snow-days in Hefei is significantly correlated with the mean winter (December–February) air temperature. The correlation coefficient and the residual standard deviation are 0.77 and 0.71°C, respectively, during the period of 1952–70. The linear regression equation is:

$$T_h = 5.06 - 0.173\ D_x \qquad (2)$$

where T_h is the mean winter air temperature in Hefei and D_x is the number of snow-days.

In addition, the winter temperature of Hefei is found to be significantly correlated to the winter temperature at the nearby Nanjing (T_n). The regression equation is $T_h = 0.09 + 1.027\ T_n$, with correlation coefficient 0.88 and the residual standard deviation 0.12°C. Given all this information, the time series of annual winter temperature of Hefei (Figure 2) is reconstructed based on the number of snow-days recorded in archives in Qing Dynasty during AD 1736–1911, the winter temperature of Nanjing during 1912–52 and the instrumental temperature of Hefei during 1952–91 (Zhou *et al.*, 1994).

Spatial representativeness

Because of the uneven (spatial and temporal) distribution of cold/warm events recorded in the historical documents, the issue of combining the individual time series into a regional mean needs to be addressed. For this, we have analysed the monthly mean temperatures for the period 1951–2000 using 20 meteorological stations evenly distributed within the region (Figure 1). Analyses indicate that temperature changes are significantly correlated among the individual stations in the middle and lower reaches of the Yellow River and Yangtze River for autumn, winter and spring. The result implies that the reconstructed historical temperature from any single site within this region may serve as a proxy of temperature changes for the whole domain. The following procedure is adopted to calculate the regional temperature from the temperature series of the individual sites.

First, the temperature anomaly series of winter half-year with the base period of 1951–80 for the domain were established.

Table 1 The shift of phenological date according to different geographical location in China

Name of plant	Phenological date	Average date in Beijing	Days/latitude
Prunus persica Stokes	Sprouting	16 February	+5.61
Ulmus pumila L.	Sprouting	27 February	+4.16
Salix babylonica L.	Budding	12 March	+3.88
Ulmus pumila L.	Beginning of flowering	22 March	+3.55
Prunus davidina Franch	Beginning of flowering	27 March	+3.28
Thuja orientalis L.	Beginning of flowering	11 April	+4.73
Prunus armeniaca L.	Beginning of flowering	4 April	+3.74
Prunus persica Stokes	Beginning of flowering	16 April	+3.98
Salix babylonica	Beginning of flowering	12 April	+3.62
Morus alba L.	Beginning of flowering	25 April	+3.09
Juglans regia L.	Beginning of flowering	26 April	+2.53
Wistaria sinesis Sweet	Beginning of flowering	29 April	+2.40
Castanea mollissima Blume	Beginning of flowering	4 June	+2.02
Albizzia julibrissin Durazz	Beginning of flowering	12 June	+2.53
Firmiana simplex W. F. Wight	Beginning of flowering	28 June	+1.06
Sophora japonica L.	Beginning of flowering	18 July	+0.72
Lagerstroemia indica L.	Beginning of flowering	19 July	+0.49
Osmanthus fragrans Lour.	Beginning of flowering	–	–2.39
Chrysanthemum indicum L.	Beginning of flowering	25 September	–3.81
Ulmus pumila L.	Shedding of all leaves	30 November	–3.62

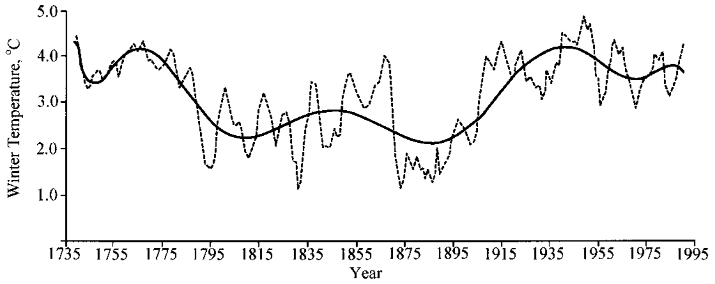

Figure 2 A reconstructed series of annual winter mean temperature during AD 1736–1991 in Hefei. Dashed line is annual winter mean temperature, and solid line is polynomial simulation.

Second, the correlation was analysed between the winter half-year temperature departure of the whole region and the seasonal temperature (autumn, winter and spring) of each station in eastern China. Finally, the significantly correlated stations/seasons were selected to establish regression equations. The regression equation is:

$$T_d = aT_{si} \qquad (3)$$

where T_d is regional mean winter-half-year temperature departure, T_{si} is the seasonal temperature departure of each station in eastern China, and a is the coefficient of the regression equation. At the same time, the correlation coefficient of the regression equation (r) was calculated. For instance, the regression equation between regional winter half-year temperature departure and the spring temperature departure of Hefei station is: $T_d = 0.47T_h$ (r = 0.56). Considering that the resolution of phenological records used in this paper is decadal to multidecadal, the regression equations were also established based on the 10-year and 30-year moving average sequences for each station. Table 2 lists the values of coefficient a for the regression equation at annual, 10-year and 30-year periods. The values are different mainly because of the different time period filtering. Further discussion will be given in the section 'Temperature reconstruction and characteristics' below.

Error analysis

There are at least three kinds of major uncertainties associated with the quantification of the cold/warm events: the ambiguity of the event description; statistical significance of the temperature correlation with phenological phenomena; and the spatial representation.

As discussed in Ge and Zhang (1990), the ambiguity of the event description involves two aspects: the identification and description of the original records and the accuracy of methods used in the subsequent process of information conversions. Considering that the original data were, piece by piece, carefully verified by experienced historians, the error associated with the first aspect is expected to be small. For the second aspect, as the conversion function or regression equation of temperature reconstruction is commonly linear, so this kind of error will be determined by the residual standard deviation (which depends on sample size, correlation coefficient and variance) and confidence level. The conversion functions have been established based on the correlation between the seasonal temperature changes of autumn, winter and spring, and information about various phenonological phenomena in some stations or the neighbouring regions from 1951 to 1980. All of the regression equations pass the significance test of $\alpha = 0.001$; the minimal correlation coefficient r is 0.55, and the maximum correlation coefficient r is 0.78. Hence, the

Table 2 Series of regression equations relating regional winter half-year temperature departures to seasonal temperature departures of individual stations in eastern China

Season	Station	Annual series		10-year moving average series		30-year moving average series	
		a	r	a	r	a	r
Spring	Beijing	0.26	0.49	0.35	0.81	0.43	0.91
	Shijiazhuang	0.33	0.52	0.77	0.72	0.85	0.90
	Ji'nan	0.29	0.56	0.28	0.76	0.28	0.91
	Xuzhou	0.35	0.48	0.42	0.48	0.74	0.81
	Zhengzhou	0.28	0.38	0.75	0.59	1.00	0.56
	Hefei	0.47	0.56	1.09	0.73	1.33	0.91
	Wuhan	0.47	0.54	1.19	0.86	1.17	0.95
	Xi'an	0.26	0.35	0.75	0.51	0.73	0.53
	Yan'an	0.35	0.49	0.87	0.70	0.94	0.87
Autumn	Beijing	0.44	0.60	0.45	0.83	0.49	0.94
	Shijiazhuang	0.50	0.65	0.75	0.88	0.73	0.94
	Ji'nan	0.34	0.67	0.26	0.84	0.27	0.94
	Xuzhou	0.52	0.64	1.12	0.78	1.40	0.92
	Zhengzhou	0.46	0.56	1.39	0.74	1.22	0.66
	Hefei	0.51	0.58	0.97	0.69	1.66	0.86
	Wuhan	0.42	0.58	0.67	0.79	0.82	0.74
	Xi'an	0.52	0.65	0.87	0.94	0.87	0.86
	Yan'an	0.46	0.60	0.77	0.90	0.77	0.96
Winter	Beijing	0.26	0.60	0.25	0.91	0.26	0.97
	Shijiazhuang	0.29	0.63	0.40	0.98	0.39	0.98
	Ji'nan	0.22	0.62	0.20	0.90	0.20	0.96
	Xuzhou	0.32	0.59	0.52	0.95	0.48	0.97
	Zhengzhou	0.32	0.56	0.58	0.94	0.66	0.93
	Hefei	0.29	0.51	0.60	0.92	0.69	0.96
	Wuhan	0.30	0.55	0.44	0.95	0.43	0.97
	Xi'an	0.34	0.58	0.59	0.95	0.56	0.97
	Yan'an	0.25	0.52	0.40	0.90	0.40	0.96

variances of sequences of temperature change for each season in those stations can be calculated. Because the correlation coefficients of the regression equations range from 0.55 to 0.78, and the sample size of sequences is regarded as 30 years, the minimal correlation coefficient 0.55 is given to be convenient in calculating the maximum error range. Thus the residual standard deviation can be estimated for the temperature change series of spring, autumn and winter of each station converted from a variety of phenological records extracted from historical documents. Finally, the maximum error ranges are calculated at the confidence levels of 80%. As shown in Table 3, the calculations indicate that this kind of statistical error ranges from ±0.5°C to ±1.4°C for each station of eastern China in spring, autumn and winter.

Finally, according to the calculations mentioned above, the residual standard deviation of conversion equation from seasonal temperature at each station to the annual winter half-year temperature of eastern China ranges from ±0.4°C to ±0.8°C. Obviously, this kind of error is quite small because the resolution of the sequences in this study is largely 30 years and partly 10 years, and is estimated to be ±0.1–0.3°C (10-year resolution) and ±0.1–0.2°C (30-year resolution) at the confidence level of 80%.

Table 3 The maximum statistical error range introduced in the conversion from phenological records into temperatures (°C)

Station	80% confidence level		
	Spring	Autumn	Winter
Beijing	±1.0	±0.6	±1.2
Shijiazhuang	±1.0	±0.6	±1.3
Ji'nan	±0.9	±0.7	±1.4
Xuzhou	±0.8	±0.6	±1.2
Zhengzhou	±0.8	±0.6	±1.2
Hefei	±0.6	±0.6	±1.1
Wuhan	±0.6	±0.7	±1.1
Xi'an	±0.8	±0.5	±1.0
Yan'an	±0.8	±0.7	±1.3

In summary, it is estimated that the total errors for the three categories mentioned above range from ±0.6°C to ±1.5°C (10-year resolution) and from ±0.7°C to ±1.5°C (30-year resolution) during the reconstruction.

Temperature reconstruction and characteristics

Since the numbers of available cold-warm records vary in time, which affects the resolution of the reconstruction, we have therefore divided the 2000 years into four periods with different temporal resolution. In addition, we have also compared our reconstruction with independent published works derived from natural proxy data to check the mutual consistency. The final 2000-year winter half-year temperature reconstruction for eastern China during the four periods is summarized below.

For the period AD 1–1500, the regional temperature is constructed at a 30-year resolution. However, for AD 961–1110, relatively abundant phenological records in Kaifeng and its neighbouring regions (Man and Zhang, 1993) make it possible to reconstruct the temperature at 10-year resolution; the reconstruction uses the methods of Wang and Wang (1990; 1991) with the newly found phenological records and the regression relation mentioned above.

For the period AD 1501–1740, many researchers used the historical records for temperature reconstruction. The time series are in the form of 'cold-warm indices' for the middle and lower reaches of the Yangtze River (Zhang, 1980); 'temperature departure' for the drainage of the Huai River (Wang and Wang, 1990) and for northern China (Wang and Wang, 1991); and 'cold-warm indices' for the middle reaches of the Yellow River (Wu and Yin, 1991). These data, in 10-year resolution, are basically consistent. Therefore, in the present study, we adopted these results, although verification of the data by the supplementary phenological evidence was carried out whenever possible.

For the period AD 1741–1950, the existing time series of annual winter temperature of Hefei within AD 1736–1980, which were reconstructed from the snow-days in Hefei from 1736 to 1911 and the instrumental data in Nanjing (nearby Hefei) from 1912 to 1952 (Zhou *et al.*, 1994), are adopted to construct the 10-year winter half-year temperature departure in eastern China using the correlative relation between Hefei and eastern China discussed earlier.

For the recent period AD 1951–99, we used the instrumental data discussed earlier to construct the 10-year resolution.

Note that the differences in the coefficient a among annual, 10-year and 30-year periods listed in Table 2 are the results of the differences in the coefficients of the individual stations. There should exist certain differences for the regional mean winter half-year temperature anomaly reconstruction based on the coefficients of different time periods of individual stations. For instance, during AD 961–1110, the difference has a range of 0.01°C (AD 991–1020) to 0.1°C (AD 1081–1110) for the reconstructed regional mean winter half-year temperature anomaly at 30-year intervals based on the regression equation coefficients of winter temperature anomaly moving average series of Zhengzhou between 10-year and 30-year periods. Similarly, during AD 1741–1950, there exist differences ranging from 0.01°C (AD 1741–70) to 0.12°C (AD 1801–30) based on the regression equation coefficients of winter temperature anomaly moving average series of Hefei. These differences are obviously smaller than the error (0.7–1.5°C) and standard deviation (0.44°C) of the winter half-year temperature anomaly series for the past 2000 years with 30-year resolution.

Figure 3 shows the reconstructed winter half-year temperature departure for the past 2000 years with 30-year resolution, as well as for the two periods AD 960–1109 and 1500–1999 with 10-year resolution. Note that, in Figure 3(a), the reference temperature (8.4°C) is the 1951–80 mean winter half-year temperature averaged over the 20 stations shown in Figure 1. As can be seen, the 30-year period is a relatively warm period for the past 2000 years.

The characteristics of the winter half-year temperature changes over the past 2000 years can be highlighted as follows.

From the beginning of the Christian era, the climate experienced a cooling trend of –0.17°C per century, and the around the AD 490s the temperature reached the lowest level of the first epoch, about 1°C colder than that of 1951–80.

Starting from the AD 510s, the temperature rose rapidly and entered the warm period of the AD 570s–1310s. In this epoch, climate was dominantly warmer, and temperature rose slowly with fluctuations with a rate of 0.04°C per century. The 30-year mean temperatures of two warm peaks were generally 0.3–0.6°C higher than present day, while a maximum warming of 0.9°C occurred during the AD 1230s–50s. For the cold troughs between the two warm peaks, the 30-year mean temperatures were generally 0.5–0.7°C lower.

After the AD 1310s, temperature decreased rapidly at a rate of 0.10°C per century. The 30-year mean temperatures of four cold troughs were generally 0.6–0.9°C colder with a maximum cooling of 1.1°C during the AD 1650s–70s. For the relative warm peaks between cold troughs, the 30-year mean temperatures were comparable to present-day temperatures.

Since the 1880s, temperature has been rising rapidly leading to the warm epoch of the twentieth century. For the most recent two decades, temperature increased dramatically. The mean temperature of 1981–99 was 0.5°C higher than that of 1951–80.

The general cold/warm trends shown in Figure 3 are consistent with the temperature changes reconstructed from other natural proxy data, such as pollen (Xia and Wang, 2000; Ren and Zhang, 1997; Tong *et al.*, 1996), stalagmitic varves (Qin *et al.*, 2000), tree rings (Liu and Shao, 2000) and lake sediments (Luo and Chen, 1997; Cao *et al.*, 2000). In addition, they also correspond very well with the environmental events that reflect temperature changes, such as the advancement or withdrawal of glacier in western China, periglacial development in northern China, and the development of palaeosoil (Zou and Wang, 1995; Zhang *et al.*, 1996; Kang *et al.*, 1991; Chen, 1987; Cui and Song, 1992; Hu *et al.*, 1991; Li and Xu, 1983; Shi, 2000; Xia, 1996). Moreover, the cold/warm trends of China during the past millennium were consistent with the Northern Hemispheric temperature variation shown in Mann *et al.* (1999). However, the contrast in the warming intensity between the twentieth century and the Mediaeval period is less in China than in the Northern Hemisphere.

Finally, one unique characteristic of the 2000-year temperature variation shown in Figure 3 is that the cold-warm and warm-cold transitions are usually rapid. For example, within a period of 90 years, temperature increased by 1.3°C in the fifth and sixth centuries (the AD 480s–500s to the 570s–590s) and decreased by 1.4°C between the thirteenth and fourteenth centuries (the 1230s–50s to the 1320s–40s). During the mid- and late nineteenth and the early twentieth centuries (the 1860s–80s to the 1920s–40s), temperature increased by 1.0°C within 60 years. Since the mid- and late nineteenth century (the 1860s–80s) to the 1980s–90s, temperature rose by 1.5°C within 110 years, and, in particular, temperature increased by 0.5°C from 1981 to 1999. It is noticeable that, although the 0.5°C rise is not the maximum temperature change of winter half-year at a 30-year resolution over the past 2000 years, which is lower only than the 0.8°C increase between AD 1201–30 and 1231–60, such a warming rate is rather rare in warm epochs. Moreover, the 0.5°C positive departure of temperature between 1981 and 1999 was close to the warmest peak of the warm epoch over the past 2000 years. If the warming continued in the next decade, the 30-year mean temperature would be expected to be higher than that in the thirteenth century, which was the highest recorded over the past 2000 years.

Our work has synthesized the methods and results of historical temperature changes conducted by many other researchers especially for the past 500-year timescale. Compared with the previous studies, indices with much more definite physical implications have been adopted in the newly reconstructed sequences, and the conversion of information is based on modern statistical relations, which greatly reduce subjectivities and uncertainties, and represent the up-to-date synthesis idea of global change studies. Comparing with the sequence of Dr Chu, who first initiated the study of cold-warm changes of the past 5000 years in China by using phenological records, the newly reconstructed sequence has made significant progress not only in the collection and verification of the original records extracted from historical documents but also in the time resolution and accuracy of data conversion.

Acknowledgements

We would like to take this opportunity to express our deep appreciation to Raymond S. Bradley for his useful comments and critical review. The research is supported by grants from the Chinese Academy of Sciences (items nos KZCX2–314, KZCX1-SW-01–09, CXIOG-A00–02 and CXIOG-E01–05-01) and a grant

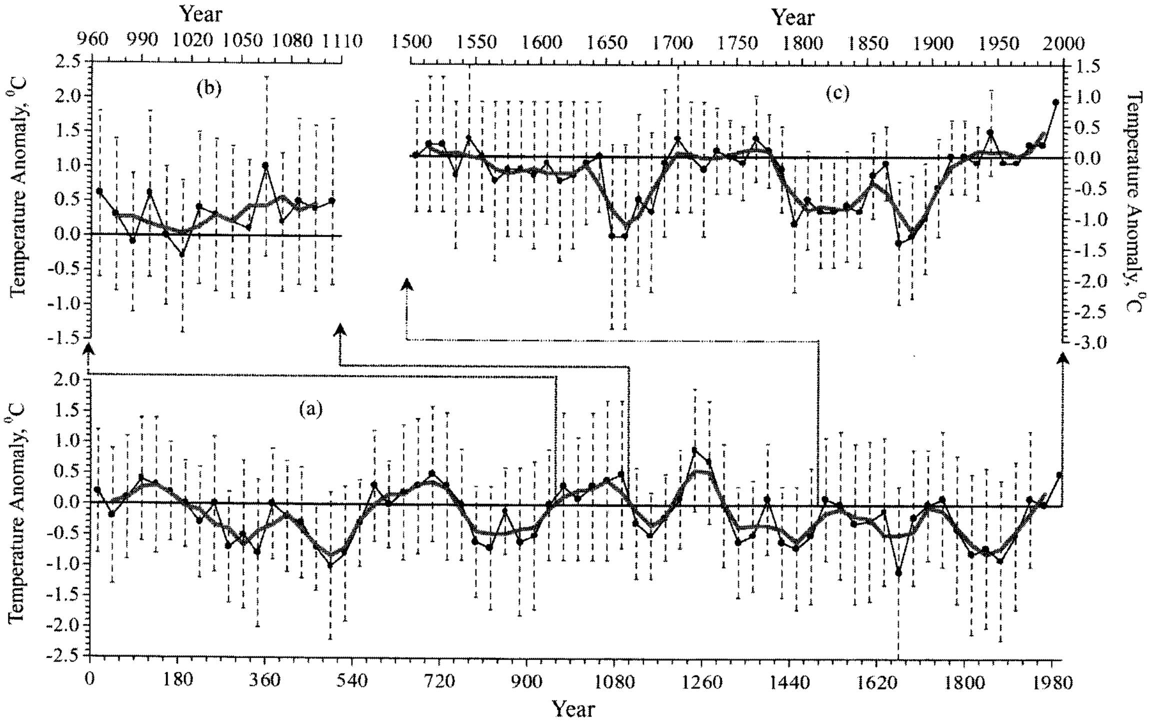

Figure 3 Winter half-year temperature anomaly change in eastern China with 30-year resolution during the past 2000 years (a), and 10-year resolution during AD 961–1110 (b) and 1501–1999 (c), respectively. Black dot line is winter half-year temperature anomaly; grey line is three-point running mean; dashed line is error bar.

from the Biological and Environmental Sciences, US Department of Energy (DOE) to SUNYA. The study is a joint research under the US DOE-PRC Ministry of Science and Technology joint agreement, 'Climate Sciences'.

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