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Climate of the Past Discussions

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Characteristics of cold-warm variation in the Hetao region and its surrounding areas in China during the past 5000 yr

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Abstract

Using six long-term temperature proxy data series derived from different natural evidences, including pollens and lake-sediments, we reconstructed a temperature series with a 100-year time resolution for the past 5000 yr in the Hetao region and its surrounding areas. The resulting series suggests that, on a millennial timescale, temperatures in the region were higher than the mean value of the whole series during the 5000~2600 yr before present (yr BP) period, and became relatively low comparing with the average temperature of the whole series after 2600 yr BP. Within these two periods, temperature fluctuations comprising numerous short, multi-centennial intervals also existed. A comparison between our reconstructed series and other series in China and across the Northern Hemisphere indicate that, on a long-term scale, cold–warm variations had been in phase across the whole hemisphere during the past 5000 yr; on the century to multi-century scale, the beginning and the ending times varied from region to region, thus implying that climate changes did not occur simultaneously in different regions.

1 Introduction

The reconstruction of temperature series for various historical periods provides important background for understanding the patterns of natural climate variability and improves our ability to assess the anthropogenic role in observed modern climate change. A number of previous studies have thus focused on climate change of past few centuries to millennium by means of modeling experiments that employ estimated climate forcing and empirical reconstructions based on climate proxy data (Mann et al., 2003).

Several recent studies emphasized spatial reconstruction of climate based on techniques for reconstruction of multivariate climate fields (Mann et al., 1998, 1999, 2003, 2008; Luterbacher et al., 2002; Evans et al., 2003; Moberg et al., 2005). These spatial reconstructions have focused on the climate changes of the past few centuries to two

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millennia on a global scale. In China, some scholars have reconstructed temperature series using an integrated method (Wang et al., 1998, 2007; Yang et al., 2002; Ge et al., 2006). The uncertainty of reconstructing climatic changes can be reduced by using the method.

The Hetao region and its surrounding areas lie in the transition zone between agriculture and animal husbandry in northern China and include areas of the Mu Us, Hobq, and Ulaan-Buh deserts. The Hetao region has an acutely vulnerable ecological environment and is sensitive to climate change. Thus, it is an ideal area for studying both east-Asian monsoon changes and global climate changes; to do so, it is important to reconstruct the past climatic variations of this region.

During the past few years, a lot of long-term, high-resolution climate proxy reconstructions with reliable millennial-scale variability have been produced for this region, which provide us proxy data to reconstruct climate change by using the integrated method. In our study, the characteristics of cold–warm variation in Hetao region and its surrounding area for the past 5000 yr are analyzed by using six long-term reconstructed temperature proxy series (Fig. 1).

2 Materials

Of the many recent studies on historic temperature variations in the Hetao region carried out, most are qualitative analyses on a century timescale; quantitative analyses on multi-century or millennial scales are relatively scarce. Following are the six long-term temperature proxy series (Table 1) selected from recent publications used in our study:

1. The average July-temperature series in the Daihai Lake (DH) reconstructed quantitatively by using model based on pollens (Xu et al., 2003). In this series, 9 samples were dated using radiocarbon-dated method. The ^{14}C age were converted to calibrated ages, then interpolated between radiocarbon-dated ages. A sampling of interval 4 cm provides a resolution is 23–158 yr in this series.

2. The oxygen isotope series of a salt lake in Yikezhaomeng, Inner Mongolia (YK) (Qian et al., 2002), which indicates temperature changes with more than 100 yr temporal resolution. In this series, 5 samples were dated using radiocarbon-dated method. The ^{14}C age were converted to calibrated ages, then interpolated between radiocarbon-dated ages.

3. The annual average temperature series, which was reconstructed by using model based on pollens in Diaojiaohaizi Lake, Inner Mongolia (DJ) (Shi et al., 2003). The Diaojiao core was subsampled at 2 cm intervals, and 111 samples were taken. In the meantime, 4 ^{14}C dates were measured, and other age data were estimated through linear interpolation between the dated horizons.

4. The total organic–carbon series in Jingbian County (JB) (Xiao et al., 2002). In the series, 11radiocarbon samples were dated using the AMS facility. The conventional ages were converted to calibrated ages. The ages of sampled horizons were derived by interpolating between radiocarbon-dated horizons. An average sedimentation rate of ca. 20 cm ka^{-1} and a sampling interval of 2 cm provide a potential temporal resolution of 100 yr.

5. The magnetic susceptibility series in Huangqihai Lake (HQH) (Shen et al., 2006), which reflects climate changes between the warm-wet and cold-arid periods. In the series, 4 radiocarbon ages were dated.

6. The carbonate-content series in Zhuyeze Lake (ZYZ) (Long et al., 2007) also reflects climate changes between the warm-wet and cold-arid periods. In this series, 11 samples were dated using the radiocarbon-dated method. The conventional ages were converted to calibrated ages. The ages of sampled horizons were derived by interpolating between radiocarbon-dated horizons.

Locations for these six series are shown in Fig. 1. The timescales of the six series are more than 5000 yr and are well-dated. Among the six series, DH and DJ

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showed temperature changes; the others depict proxy temperature changes with different proxy records. 6 reconstructions from different proxy archives represent temperature changes and explain between 83% and 94% of annual temperature variability in 1951–2007.

For the sake of transferring and comparing data, we used the annual surface-temperature grid-point (1 latitude×1 longitude) data set in 1951–2007 in China (http://cdc.cma.gov.cn/) for analysis. This data set was obtained using the Spatial Kriging Interpolation Method based on average monthly temperature and DEM (digital elevation model) materials of 731 stations throughout China.

3 Methods

Two ways to reconstruct regional paleo-temperature series under the constraint of insufficient data were commonly used in previously published articles: computing the average of all available proxy series in a study area (Jones et al., 1999; Crowley and Lowery, 2000) using a data set that is relatively small and heterogeneous; merging proxy records of several sub-regions by a specific area weighting (Wang et al., 2000; Yang et al., 2002). The latter method has recently been widely used for regional, hemispheric, and global climate reconstructions (Bradley et al., 1993; Jones et al., 1998; Mann et al., 1998, 1999, 2003; Moberg et al., 2005). This method emphasizes a synthesis of different types of proxies derived from various local regions having differing temporal resolutions. The integrated results show some important climate features not derived from one type of proxy records or from proxies with identical temporal resolutions. To some extent, the multi-proxy analysis method can thus reduce uncertainties in proxy-based climate reconstructions.

Taking the actual background of the study area into consideration, we developed an improved method to reconstruct the regional temperature series of the small Hetao region.

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First we calculated the series of annual temperatures for the whole region (WT) of Hetao and neighboring areas according to the surface annual–temperature grid data during 1951–2007 for China (Eq. 1). We next calculated the correlation between WT and the annual temperature series in each grid area; this correlation is considered as a contribution to the entire region. The total value (TV) is the sum of the grid contributions provided by each of the series (Eq. 2); the weighted value is the ratio of the contribution value of one series to the TV (Eq. 3). Finally, based on the weighted values of the grids, the following weighted-average equation was adopted to combine the six series into the whole regional temperature series (Eq. 4). The equations are as follows:

$$\mathrm{WT} = \sum_{i=1}^{n} T_i / n \tag{1}$$

Where WT is the series of annual temperatures for the whole region according to the surface annual–temperature grid data during 1951–2007 for China; T_i is the temperature of each grid and n is the numbers of grid.

$$\mathrm{TV} = \sum_{i=1}^{n} r_i \tag{2}$$

Where TV is the sum of r and r_i is the correlation between WT and T_i.

$$S_i = r_i / \mathrm{TV} \tag{3}$$

Where S_i is the area's weighted value.

$$T_\mathrm{w} = \sum_{i=1}^{n} T_i S_i \tag{4}$$

Where T_w is the whole regional temperature and T_i is the temperature of each sub-region.

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Before averaging, each series is standardized; this gives the relative amplitude of temperature change, as shown in Fig. 2. The three steps of the method for standardizing are as follows:

(1) Selecting samples – According to the correlative papers, the reconstructed data of all but the DH series were obtained by digitizing. All of the abrupt climate change points in each series were taken as random samples to reconstruct the whole region series.

(2) Calibrating the ^{14}C ages into calendar ages – using the calib5.0 program (Stuiver et al., 1998), the six series were all converted to calendar chronological series.

(3) Making the series dimensionless – each series was standardized to a dimensionless series that reflected the climate variation amplitude.

In the six series we selected, the time resolution of one is less than 100 yr, one is no more than 100 yr, and others are more than 100 yr. Accordingly, the past 5000 yr was divided into 100-yr intervals. For every series we selected, we calculated the average of all data within each 100-yr period if the series resolution was not more than 100 yr and by linear interpolation between existing data if the series resolution was more than 100 yr. Finally, a series that indicates temperature variation (weighted average, WA) was acquired according to the methods previously described (as depicted in Fig. 3).

4 Results and discussion

Figure 3 shows that the change trend of CA (arithmetic average) is very consistent with that of WA, with the only differences being the values of original data. In the past 5000 yr and on the millennial scale, variations in temperature were warm in 5000~2600 cal yr BP and were colder after 2600 cal yr BP. Within these two periods, the temperature fluctuated, and there existed numerous short, multi-century sub-stages. We divided the 5000 yr into following seven periods according to cold–warm variations.

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(1) 5000~4500 yr BP: This period was the end of the Holocene Megathermal Maximum Age. The temperature was higher than the mean value of the whole series in Hetao and its neighboring areas. Obvious evidence of this are in Diaojiaohaizi Lake (DJ), Yikezhaomeng salt lake (YM), Daihai Lake (DH) and Jingbian County (JB) of China (Fig. 2). Other domestic studies have validated the existence of this warm sub-stage. The temperature series reconstructed by Chu (1973) showed that in China, during this period, it was warm and humid in the Poyanghu Lake area of Jiangxi Province (Peng et al., 2003), in the Zhengzhou area of Henan Province (Wang et al., 2004), in the Hanihu Lake area of Jilin Province (Cui et al., 2006), and in Dunde ice core in Qinghai Province (Yao et al., 1992). These facts are also corroborated by many world-wide studies. It was proved that the climate during this period was warm in the north of Iceland (Axford et al., 2007) and in the area of the North Atlantic (Bond et al., 2001).

(2) 4500~3900 yr BP: The temperature decreased in the study area and reached the lowest of during this time period at 4300 cal yr BP. This cold event was very obvious in Daihai Lake (DH) and Diaojiaohaizi Lake (DJ) in China (Fig. 2). Other facts suggest that the cold event was global. Jin et al. (2002) proved that the cold event happened in the north China during 4800~4200 cal yr BP; Zhang et al. (1997) found out that the mean temperature during that cold event period was about 3 °C lower than the present temperature in the transition zone between agriculture and husbandry areas in China; Lv (1991) deduced that the climate obviously turned cold at about 4.2 kyr BP (^{14}C) in the north of China; Shao et al. (2006) proved a cold and arid event at 4.3 cal kyr BP in the Shennongjia area of Hubei Province by means of an oxygen isotope series in a stalagmite; Bond et al. (1997) discovered an ice-floating event in the North Atlantic Ocean during this time period; and Hong et al. (2003) found that the Indian monsoon weakened suddenly at about 4.3 kyr BP.

(3) 3900~2600 cal yr BP: The temperature was relatively high compare with the mean value of the whole series as showing in Jingbian (JB) and Daihai lake area (DH) (Fig. 2). In addition, the $\delta^{18}O$ and pollens appearing in peat in Taishizhuang village gave evidence of a very warm event during 4.2~3.38 cal kyr BP in the northern

Huabei area of China (Jin et al., 2002); the Indian summer monsoon was very strong at the same time (Hong et al., 2003); the climate was very warm at about 2.5 kyr BP in Fennoscandia region, Finland (Seppä et al., 2002).

(4) 2600~1450 cal yr BP: The temperature decreased rapidly and lower than the mean value of the whole series; that was very obvious in Jingbian area (JB) during this time period (see Fig. 2). Parallel evidence abounds: The lake-sediment record in Jiaming Lake showed that the climate turned cold after 2.2 kyr BP in southern Taiwan (Luo et al., 1997); The climate was also cold during 2550~1211 yr BP in Ulaan-Buh Desert of China (Jia et al., 2003); The strata in Hunshandake Desert of China show an abundance of Aeolian sand at about 1.8~1.3 cal kyr BP, thus giving evidence of a cold climate (Jin et al, 2004); The Guliya ice core and tree-ring records in China show that the climate was cold at 0 AD (Yao et al., 2001); The winter half-year temperature was relatively low during 1700~1400 yr BP in eastern China (Ge et al., 2003); The yearly average temperature was low in the Tibet plateau region during the period (Yang et al., 2003); A cold event during 1.8~1.4 kyr BP had been recorded in the southern deep sea off Iceland (Bianchi et al., 1999); An ice-floating event appeared in the North Atlantic Ocean at 1.4 kyr BP (Bond et al., 1997).

(5) 1450~1000 cal yr BP: The climate was relatively warm compare with the temperature of its adjacent periods but less so than the degree of warmth at 5000 cal yr BP. This period corresponded to the Medieval Warm Period. Following are *p* proofs that give examples: A warming event happened in Daihai Lake in the southern part of the study region during 1.2~0.9 kyr BP (Jin et al., 2002); The Dunde ice core indicated that there was a climate warming phase during the 13th century (Yao et al., 1992); The Guliya ice core recorded a warm event in 1250~1150 cal yr BP (Yao et al., 1996); At the Chesapeake Dam, the Medieval Warm Period began at 1150 cal yr BP (Cronin TM et al., 2003), which was earlier than the period began in other areas in the world.

(6) 1000~300 cal yr BP: the temperature decreased again. this period includes the Little Ice Age. Temperature of the lake water of Daihai Lake was low during 2010–300 yr BP (Shen et al., 2002). Aeolian sand deposited in Hunshandake Desert during

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700–200 yr BP produced a record of the cold event, which took place at about 400 yr BP (Jin et al., 2004).

(7) 300 cal yr BP to present: The climate has been warming. Shen et al. (2002) found out that the water temperature in Daihai Lake had been rapidly warming since 300 yr BP, increasing from 16.2 °C to 17.5 °C.

5 Conclusions

The air temperature, on the millennial scale variation, was relatively high compare with the mean value of the whole series during 5000~2600 cal yr BP and decreased after 2600 cal yr BP. Many temperature fluctuations took place during those two periods. During the periods of 5000~4500 cal yr BP, 3900~2600 cal yr BP, 1450~1000 cal yr BP, and 300 cal yr BP to present, the temperature was warm; while during the periods of 4500~3900 cal yr BP, 2600~1450 cal yr BP, and 1000~300 cal yr BP, the temperature decreased.

The cold–warm variation of climate on long-term scale disclosed by the reconstructed series described in this paper took place in phase with that proved in other global research efforts. However, on the century to multi-century scale, the beginning and the ending times varied from region to region, thus implying that climate changes did not occur simultaneously in different regions.

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Table 1. Information regarding the six series applied.

No.	Site or region	Proxy type and interpretation	Resolution (years' time span)	First, last year (yr BP)	Age type	Calibrated time (Cal. yr BP)
1	Daihai Lake (DH) 40° N, 112° E	Pollen, Jul T [a]	23–158	12 000–0	Cal. [b]	12 000–0
2	Yikezhaomeng salt lake (YK) 39° N, 109° E	Lake sediment, $\delta^{18}O$	>100	16 000–0	^{14}C [c]	19 091–0
3	Diaojiaohaizi Lake (DJ) 41° N, 112° E	Pollen; annual average T	>100	10 000–2000	^{14}C	11 471–1946
4	Jingbian County (JB) 37° N, 108° E	Total Organic–Carbon	100	10 000-0	Cal.	10 000–0
5	Huangqihai Lake (HQH) 41° N, 113° E	Lake sediment; magnetic susceptibility	<100	9000–2000	^{14}C	10 200–1946
6	Zhuyeze Lake (LZL) 39° N, 103° E	Lake sediment; content of carbonate	<100	9000–3000	Cal.	9000–3000

Notes: [a] T represents temperature; [b] Cal. represents the series chronological control provided by calendar ages; [c] ^{14}C represents the series as chronologically controlled by ^{14}C ages.

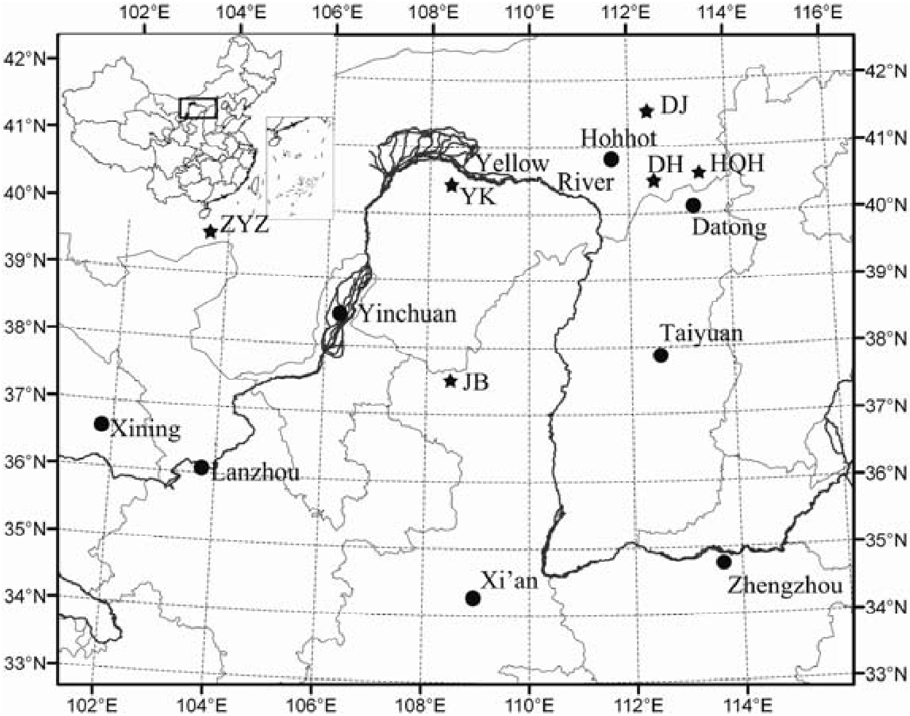

Fig. 1. Distribution map for six locations of proxy climate records (stars=the site of proxy climate records; dots=primary cities).

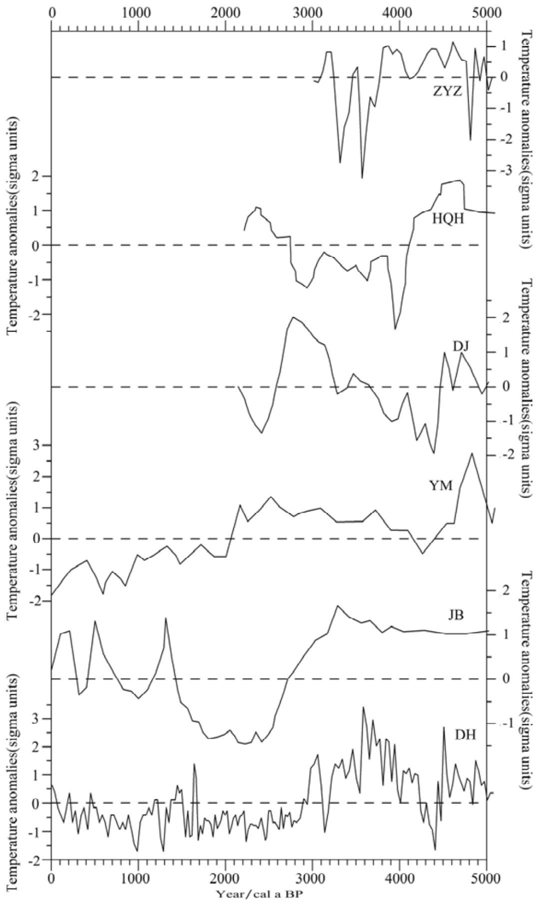

Fig. 2. Standardized 5000-yr regional temperature series for Hetao region and its vicinity.

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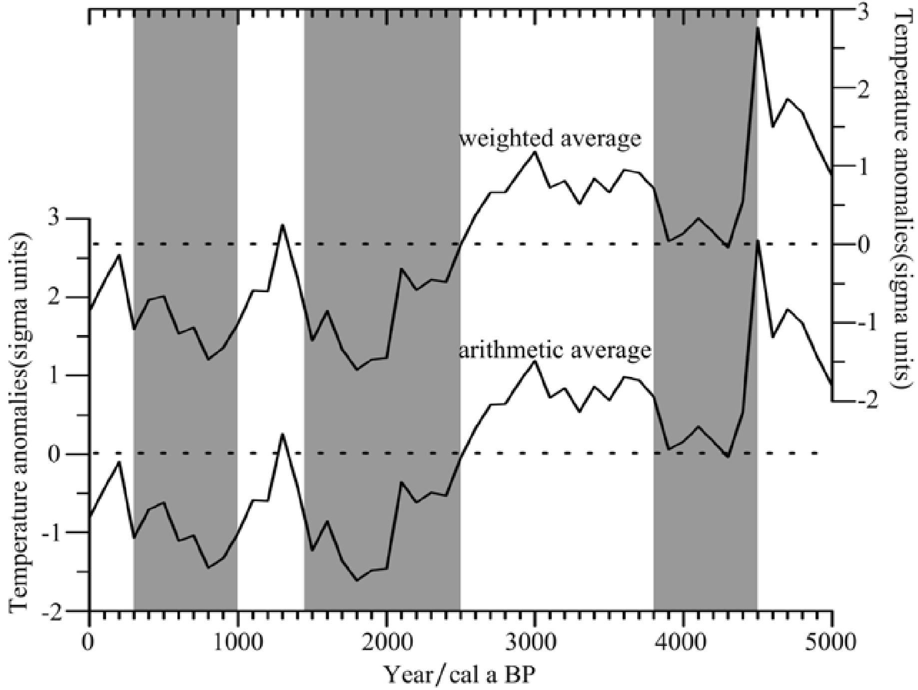

Fig. 3. Temperature reconstructions in Hetao region and neighboring area.

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