Temperature variations in the past 6000 years inferred from $\delta^{18}O$ of peat cellulose from Hongyuan, China

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Abstract **Trends of the temperature variations recorded in $\delta^{18}O$ in Hongyuan peat cellulose are similar to those recorded in $\delta^{18}O$ of Jinchuan peat cellulose and in $\delta^{18}O$ of Dunde ice core. Climate events have been identified to be globally homogeneous. Two notable climate transition periods have been detected in the past 6000 years, namely 4000 aBP with climate shifting from cold to warm and 1500 aBP with climate shifting from warm to relatively cold. Power spectrum analysis was performed to investigate the periodical signals in the $\delta^{18}O$ time series. Typical periodicities of 1200—1087 a, 752 a, 444 a, 325 a, 213 a, 127—123 a, 88 a, 79 a were discovered, indicating an integrated influence on Hongyuan climate from solar, monsoon and ocean activities. Solar forcing has been addressed to be the main driving forcing of Hongyuan climate.**

Keywords: Hongyuan, oxygen isotopic composition, peat, temperature.

Many researchers have identified climatic teleconnections of the globe, especially those of the Northern Hemisphere. Bond et al.[1] discovered such teleconnections between the climate inferred from sedimentary matters in Atlantic and that recorded in Greenland ice core. Porter and An[2] proved that the variations of East Asian monsoon inferred from the Chinese loess were highly correlated with the Heinrich events identified in Atlantic. The monsoon activity in the subtropical region recorded in the Arabian Sea sediments also corresponds well with the climate variations at the high-latitudes[3]. The Holocene climate has been documented to be instable through numerous high-resolution climatic proxy indicators established in recent years[1,4,5]. A general picture of global climate changes during the Holocene has been figured out. However, much work needs to be done to shed much light on the climate variability and to constrain the causes/mechanisms of climate changes.

High-resolution climatic proxies are the fundamental tools for investigating the causes/mechanisms of climate changes. They would be helpful to go into the details of climate changes in the past, deduce the causes/mechanisms of the climate system and predict climate variability in the future, which has been highlighted by the PAGES and CLIVAR Workshop[6]. In China, much attention has been paid to the high-resolution climate changes following the mid-Holocene[7—9], with the purpose to reconstruct a high-resolution climate variations profile in the past several thousands of years and to compare the research results from climate proxies with the long ancient civilizations of China.

The oxygen isotopic composition of plant cellulose has been documented to reflect oxygen isotope ratios in the environmental waters sensitively[9—12], which correlates significantly with climate parameters, especially temperature[13,14]. Hence, the palaeoclimate can be reconstructed from oxygen isotope ratios in plant cellulose. Peat deposits have been proved to be a perfect climate variation archive due to advantages such as high resolution, relatively large time scale and sensitivities to climate changes[9,12,15—17]. Here we report a high-resolution trend of temperature variations in the past 6000 years inferred from $\delta^{18}O$ of peat cellulose in Hongyuan, China. The results indicate that temperature variation trend in Hongyuan in the past 6000 years is similar to those in other areas of China and that the temperature events are highly correspondent to those all over the world. Power spectrum analysis was performed to investigate the causes/mechanisms of Hongyuan climate changes.

1 Sampling and method

The sampling site (32° 46′N, 102° 30′E) is located in the west of Hongyuan County at the northeastern edge of the Qinghai-Tibetan Plateau. Climate in Hongyuan is cool to cold, belonging to the continental plateau monsoon climate type. Winter is long, cold and dry, with strong wind and heavy snow. Summer and autumn are warm and moist, with plentiful rainfalls and hails. The highest and lowest temperatures are distributed in July and January, respectively. Solar irradiance is strong[18]. The sampling site is 3466 m a.s.l.

^{14}C dating was performed on the accelerating mass spectrometer at the NIES of Japan[19]. The ^{14}C ages were carefully calibrated with the computer program of CALIB 4.3[20]. Another ^{14}C age calibrating software of INTCAL 98[21] was chosen to verify the calibrating result from CALIB 4.3. The results are listed in fig. 1 and the calibrating result from CALIB 4.3 was chosen in our note.

Alpha-cellulose was extracted from peat samples using the standard Jimmy-Wise method[22]. Oxygen isotopic composition was measured using the improved nickel pyrolysis technique[23,24]. Standard alpha-cellulose samples from IAEA were used in our experiment to monitor the precision and the accuracy. The oxygen isotopic composition is expressed against SMOW in the standard "δ^{18}O" notation, where

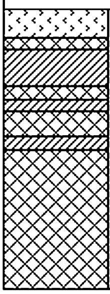
$$\delta^{18}\mathrm{O}(‰)=\left[\frac{\left({}^{18}\mathrm{O}/{}^{16}\mathrm{O}\right)_{\mathrm{sample}}-({}^{18}\mathrm{O}/{}^{16}\mathrm{O})_{\mathrm{standard}}}{({}^{18}\mathrm{O}/{}^{16}\mathrm{O})_{\mathrm{standard}}}\right]\times 1000.$$

Experimental work was carried out at the State Key Laboratory of Environmental Geochemistry, the Chinese Academy of Sciences, with an error less than $\pm 0.2‰$.

Fig. 2 presents the δ^{18}O series in the past 6000 years.

2 Temperature variations in the past 6000 years inferred from δ^{18}O

The oxygen isotope ratio of peat cellulose has been proved to be an excellent temperature proxy indictor[9,12]. The black shadow indicates the trend of Hongyuan temperature variations inferred from $\Delta\delta^{18}$O (fig. 3). Temperature variation trend of Jinchuan[9] and those of Dunde[25] and Greenland[26] are also shown in fig. 3. Three obvious periods can be distinguished from the past 6000 years temperature trends of Hongyuan, Jinchuan and Dunde, namely 6000—4000 aBP with low temperature conditions, 4000—1500 aBP with high temperature conditions and 1500—0 aBP with relatively low temperature conditions. 4000a BP and 1500a BP or so can be regardedas two climatic transitions. At about 4000 aBP, temperature shifted from low level to high level, at 1500 aBP, temperature shifted from high level to relatively low level. A similar climate transition can also be detected in the $\Delta\delta^{18}$O series of the Greenland at about 1500 aBP.



Stratigraphy	Sample No.	Depth /cm	δ^{13}C (‰, PDB)	AMS^{14}C age/aBP(1σ)	Calibrated age/aBP(1σ) Calib 4.3	Intcal 98
	HY38	38	−27.37	1291±61	1243	1200
	HY64	64	−26.87	1790±76	1710	1711
	HY78	78	−27.25	2088±42	2043	2056
	HY105	105	−27.59	3642±44	3945	3971
	HY130	130	−27.35	4148±44	4690	4688
	HY160	160	−27.47	5304±48	6091	6078
	HY220	220	−28.06	6430±42	7367	7353

Modern grass root   Yellowish-brown peat   Brownish-black herbal peat

Fig. 1. Hongyuan peat deposit profile and its ^{14}C dates.

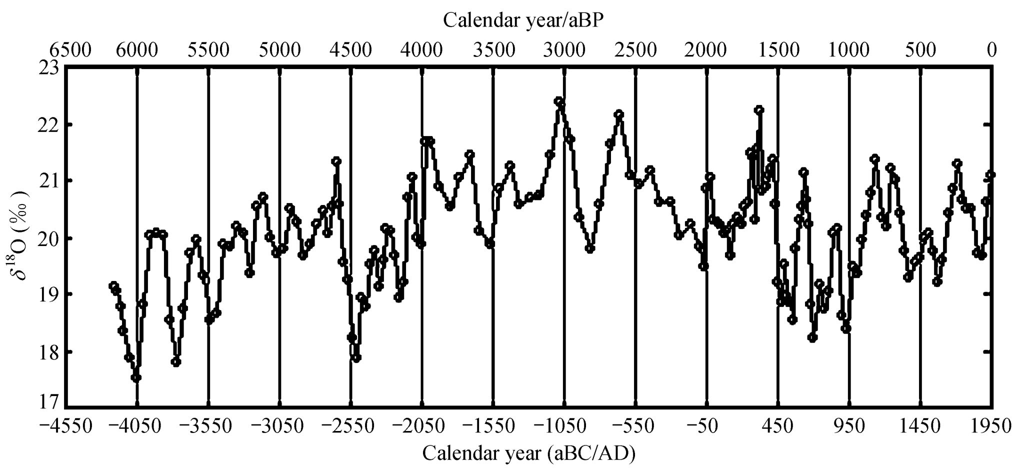


Fig. 2. Oxygen isotopic composition of Hongyuan peat cellulose.

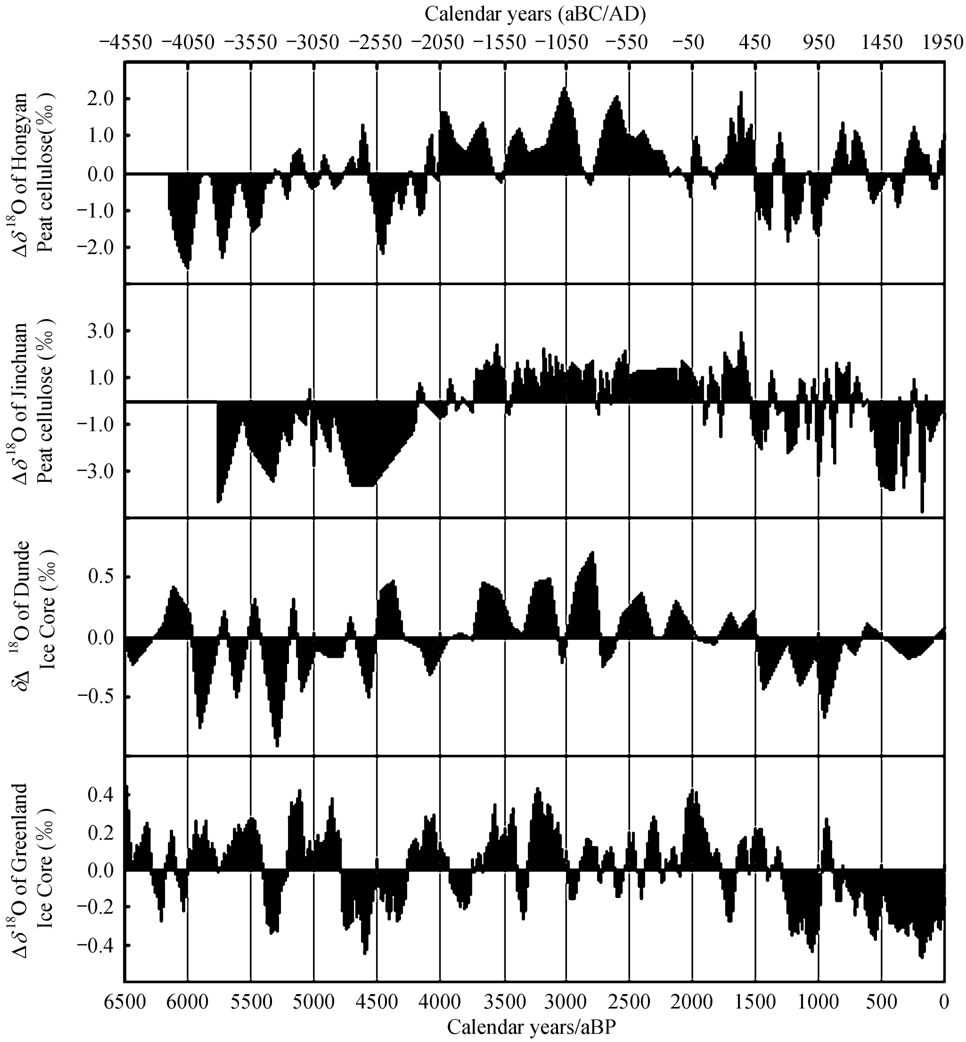


Fig. 3. Comparison of the oxygen isotopic compositions between Hongyuan, Jinchuan, Dunde and Greenland.

(i) Temperature varied at a low level during 6000—4000 aBP. Fig. 3 indicates that temperature varied at a low level in Hongyuan, Jinchuan and Dunde during 6000—4000 aBP. This cold period can also be deduced from historical records and archaeological discoveries[25]. The number of the cites of ancient Chinese civilization during this period is seriously less than that before or later in the Yangtze River and Huang River basins[25]. This cold period coincides with the cold conditions in North America and Europe[27], tropical Pacific regions, Australia and South America[28], etc., corresponding to the cold climate conditions during the mid-Holocene[27,28].

The $\Delta\delta^{18}$O series indicates a strong temperature decrease at about 6000 aBP in Hongyuan. Obvious temperature drops also existed in Dunde at 5900 aBP and in Greenland at 6030 aBP. Strong temperature drops can also be observed in the δ^{18}O series of the sediments in Sumix Co[29] at 6000 aBP. The δ^{18}O series in the stalagmites in Qixing cave, Guizhou[30] indicates a strong decrease at 6000 aBP. In North Atlantic, a strong drop occurred at 6000 aBP in the ice rafted debris series[1], suggesting a temperature decrease at this period. This cold event can also be identified from the δ^{18}O series of the sediments in Arabian Seas[4].

Two cold events occurred at about 5700 aBP and 5450 aBP, corresponding to "The Second Global Neo Ice Age" [27]. These cold events existed both in Jinchuan[9,12] and in Dunde[25].

A remarkable period of 4600—4200 aBP with a dramatical temperature decrease was recorded in the δ^{18}O series of Hongyuan peat cellulose. This cold event lasted long, with strong amplitudes nearly similar to the temperature decreasing magnitudes of the Younger Dryas inferred from the carbon isotope ratios in Hongyuan peat cellulose (to be published). This remarkable cold event was recorded in Jinchuan[9,12] during 4700—4300 aBP, with a similar time scale and similar amplitude. Both the $\delta^{18}O$ series of peat cellulose and pollen records in the peat in Taishi Zhuang, Hebei[31] indicate a strong temperature decrease during 4800—4200 aBP. A strong decrease was also recorded in the $\delta^{18}O$ series of the sediments in Sumix Co[29] at 4300 aBP. In Greenland[26], a strong temperature decrease occurred during 4800—4300 aBP, and in the Alpines[32] a temperature drop occurred during 4800—4500 aBP. In Sahara, nearly all the freshwater lakes desiccated during this period of time and the ancient Sahara civilization came to an end. The specially dry and cold climate conditions forced the resident to change their settlements in North Mesopotamia, and the Akkadian Empire in South Mesopotamian collapsed. The ancient civilizations both in the Indian River valley and in Egypt collapsed synchronously in that cold-dry period of time[33,34].

(ii) Temperature varied at a high level during 4000—1500 aBP. Temperature varied at a relatively high level during 4000—1500 aBP, just like the temperature variation trends in Jinchuan and Dunde. Numerous archaeological and historical matters that recorded the warm conditions in this period have been provided[25]. Evidence proves that during this warm period the ancient Chinese civilizations of the Yangtze River and the Huang River basins developed rapidly[31]. The ancient China witnessed a transition from Neolithic Age to Bronze Age and had created its first character on bones or tortoise shells, one of the oldest scripts in the world and the precursor to the contemporary Chinese character set[9,12]. More than 100000 pieces of oracle inscription were discovered in Yin Xu, capital of the Shang Dynasty (3550—2950 aBP). Descriptions on those oracles revealed a relatively warm climate during this period of time[9,12,35]. This warm period can also be derived from botanical evidence[36] that the total arboreal pollen content increased obviously and the total pollen content of the hydrophytes decreased, implying warm and dry climatic conditions.

Several significant and globally distributed cold events occurred in the warm period of 4000—1500 aBP. A decrease occurred around 3600—3500 aBP. This cold event occurred at about 3400a BP in Dunde[25] and Greenland[26]. The carbon and oxygen isotopic compositions of the cave speleothem calcite in North America[37] indicate a strong temperature decrease at about 3600 aBP, with an amplitude of nearly 4℃. Another strong cold event was recorded in Hongyuan during 2900—2700 aBP. This cold event occurred during 2800—2700 aBP in Dunde[25]. Materials extracted from historical literature[38] suggest a very cold and dry climate during 2850—2750 aBP in China. The ancient book *Bamboo* recorded that during the periods of 857—853 aBC, 828 aBC, 803 aBC, and 780 aBC there had been prevailing a cold and dry climate. Many rivers, especially the Jing River, the Wei River and the Luo River, dried out. The cold-dry condition lasted for nearly 77 years. This special event was named the “King-Li Draught and Rivers Desiccating Event” by Lu et al.[38] Van Geel et al.[39] documented particularly to reveal this cold-dry event world widely, including evidence from Europe, North America, South America, New Zealand, Japan, Caribbean, and many regions in tropical Africa.

Following the so-called “King-Li Draught and Rivers Desiccating Event”, temperature rose and immediately dropped, reaching a valley at about (2000±100) aBP. Then temperature rose again, reaching an apex at about 1680 aBP and lasting till 1530 aBP. During the North-South Dynasty there appeared another cold event at 1530—1370 aBP. In this period, icehouses could be established at the city of JianYe[7] (named Nanjing City, one of the three hottest cities in China at present), which is impossible today using the backward techniques of that time, implying a very cold climate at that time.

Attention should be paid to the warm period of 1690—1530 aBP (270—420 aAD), in Hongyuan, Jinchuan and Dunde. Most of the previous studies recognized the period of 2000—1500 aBP as a cold period arbitrarily, neglecting the warm period of 1690—1530 aBP.

(iii) Temperature was relatively low during 1500—0 aBP. Temperature varied at a relatively low level during 1500—0 aBP. This trend can be observed in Jinchuan, Dunde and Greenland. Chu[7] first put forward the concept of “Sui-Tang Warm Period” in China during 1350—1050 aBP (600—900 aAD), addressing warm climate conditions mainly from historical materials. This warm period, however, neither occurred in Hongyuan, nor in Jinchuan or Dunde. The $\delta^{18}O$ series of Guliya ice core[40] with a 10-a resolution, did not record the warm conditions of the “Sui-Tang Warm Period”. On the contrary, three consistently cold events, namely 500 aAD, 700 aAD, 900 aAD, exist in Hongyuan, Jinchuan and Dunde, suggesting that the “Sui-Tang Warm Period” may not exist in some regions of China.

During 1100—1300 aAD, the $\delta^{18}O$ of Hongyuan peat cellulose increased, consistent with that of Jinchuan peat cellulose and corresponding to the “Medieval Warm Period” (MWP)[41]. However, there has a long-standing controversy over the existence of the MWP in China. Man[42] discovered that the north boundary of some plants such as rice, sugarcane, tea plant, citrus and flux, is 1° northward relative to that of today, indicating a warmer climate at that time. Zhang[43] discovered that the living region of some perennial plants such as citrus and flux expanded northward during the tenth to thirteenth centuries and reached their north boundary at the thirteenth century. However, Chu[7] pointed out that the MWP did not exist in China and there were no footprints of MWP in the Dunde ice core and Guliya ice core. However, Huang and Pollak[44] have proved that the MWP was globally distributed, based on the evidence of Earth surface temperature from 6144 sites worldwide. Broecker[45] emphasized that the MWP exists globally and the different amplitudes in different regions are related to the sensitivity of the proxy indicators.

The periods of 1370—1400 aAD, 1550—1610 aAD, 1780—1880 aAD recorded three cold events, corresponding to the "Little Ice Age" (LIA)[46,47]. Divergence exists in China concerning the starting and ending time of LIA. Chu[7] pointed out 3 cold events in LIA, namely 1470—1550 aAD, 1620—1720 aAD, 1840—1890 aAD. These three cold events occurred at 1450—1550 aAD, 1600—1690 aAD, 1790—1880 aAD in Dunde[25] and 1550 aAD, 1650 aAD, 1750 aAD in Jinchuan[9,12]. LIA was recorded in Guliya ice core[40] during 1510—1920 aAD.

3 Driving forcing of climate change in Hongyuan

Power spectrum analysis was performed to investigate the driving forcing of climate change in Hongyuan,

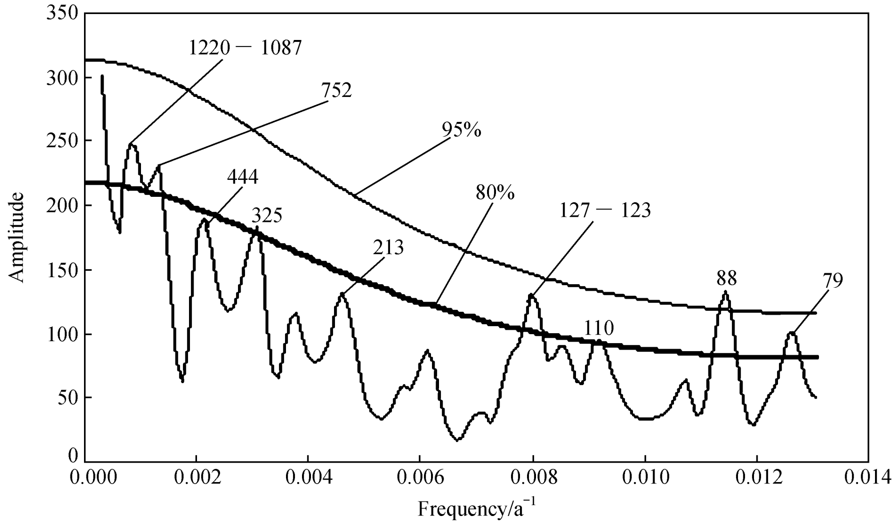


Fig. 4. Power spectrum analysis results of Hongyuan δ^{18}O series.

which, as has been discussed above, shows almost the same temperature trend with those of Jinchuan and Dunde, and is in good consistence with those in other parts of the world. The computer software REDFIT35[48], which has been proved to have a high performance in power spectrum analysis for unevenly spaced time series, is used in our work. Default parameters are used except that the parameter of n_{50} representing the Welch-Overlap-Segment-Averaging (WOSA) is 4 and Welch spectrum window is chosen (refer to ref. [48] for details). Results are presented in fig. 4.

Periodical signals of 79 a, 88 a, 110 a, 123—127 a are detected, which reflect the influence of solar activity. A remarkable periodicity of 213 a is discovered with a relatively low confidence level, which, however, is exhibited strongly in the total organic carbon content[49] time series in Hongyuan peat and coincides with the periodicity of 207 a in the δ^{18}O series of Jinchuan peat cellulose. The periodicities of 325 and 752 correspond to the solar activity function (T=11×2^n) at the fifth (352 a) and the sixth (704 a) levels. The periodicities of 1220—1087 a[1—5] coincide with the millennium time scale periodicity of the Holocene. A similar periodicity of 1046 a exists in Jinchuan δ^{18}O series. The periodicity of 444 a, however, cannot be interpreted theoretically although it has also been detected in the total organic content series of Hongyuan peat[49].

The periodicities of 79 a, 88 a, 123—127 a in Hongyuan have the highest confidence level among all of the periodicities, suggesting that the main driving force of Hongyuan climate change is from solar activities. However, climatic driving force at Hongyuan is complex because this region is influenced by southeast monsoon, southwest monsoon and the winter monsoon of East Asia. The oceans can transfer their signals to the atmosphere by the ocean-atmosphere coupling process. Then those oceanic signals can be brought to the main continent of China by monsoons. The periodicity of 775 a has been discovered in the sea surface salinity (SSS) series in the South China Sea[50]. Periodicities of 1020—1150 a in REE series, 1150 a in Ca content series and 1120 a in globigerina grain content series have been discovered in the study of Arabian Sea sedimentary records[3]. Numerous evidence demonstrated this typical quasi-millennium oscillation in the oceanic system[51,52]. The periodicities of 752 a and

1087—1220 a in Hongyuan may be the reflections of oceanic activities from the South China Sea and those from the Arabian Sea, respectively. However, it is too early to make any further conclusion before more work is done.

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