Response of climate to solar forcing recorded in a 6000-year δ^{18}O time-series of Chinese peat cellulose

Y.T. Hong,[1] H.B. Jiang,[1] T.S. Liu,[2] L.P. Zhou,[3] J. Beer,[4] H.D. Li,[5] X.T. Leng,[5] B. Hong[1] and X.G. Qin[2]

([1]State Key Laboratory of Environmental Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences, Guiyang, Guizhou, 550002, China; [2]Institute of Geology, Chinese Academy of Sciences, PO Box 9825, Beijing, 100029, China; [3]The Godwin Laboratory, Department of Earth Sciences, University of Cambridge, Pembroke Street, Cambridge CB2 3SA, UK; [4]EAWAG, Ueberlandstrasse, 133, CH-8600, Duebendorf, Switzerland; [5]Institute of Peatmire, Northeast Normal University, Changchun, Jilin, 130024, China)

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Abstract: Previous studies have shown that the oxygen isotope ratio (δ^{18}O) of plant cellulose can serve as a sensitive proxy indicator of past climate, but its application has mainly been restricted to tree-rings. Here we present a 6000-year high-resolution δ^{18}O record of peat plant cellulose from northeastern China. The δ^{18}O variation is interpreted as reflecting changes in regional surface air temperature. The climate events inferred from the isotope data agree well with archaeological and historic evidence. The record shows a striking correspondence of climate events to nearly all of the apparent solar activity changes characterized by the atmospheric radiocarbon in tree-rings over the past 6000 years. Spectral analysis of the δ^{18}O record reveals the periodicities of around 86, 93, 101, 110, 127, 132, 140, 155, 207, 245, 311, 590, 820 and 1046 years, which are similar to those detected in the solar excursions. We consider these observations as further evidence for a close relationship between solar activity and climate variations on timescales of decades to centuries. Our results also have implications for distinguishing between natural and anthropogenic contributions to future climate change.

Key words: Solar forcing, peat, δ^{18}O, climatic change, global warming, radiocarbon anomalies, Holocene, China.

Introduction

There has been a number of investigations of the possible link between long-term climate variability and solar activity (Suess, 1968; Denton and Karlén, 1973; Magny, 1993; Stuiver and Braziunas, 1993; Chambers *et al.*, 1999). The history of solar variability can be derived from the ^{14}C content in tree-rings (Stuiver and Quay, 1980; Stuiver, 1980). Based on the historic records and radiocarbon in tree-rings, Eddy (1976; 1977) inferred 18 apparent long-term changes in the level of solar activity during the past 7500 years. He suggested that, in every case where the long-term solar activity falls, mid-latitude glaciers advance and the climate cools, whereas at time of high solar activity glaciers recede and climate warms. Wigley and Kelly (1990) introduced an index of solar activity, i.e., ^{14}C anomaly, obtained from the difference between the dendro-age and the ^{14}C age of tree-rings, to characterize the changes in solar irradiation. They found a significant correlation between climatic records from both hemispheres and ^{14}C anomalies. More recent investigations on pro-glacial lacustrine sediments and alpine-glacial moraines, as well as plant composition of raised bogs, show a good correspondence between the timing of the past major cold events in Scandinavia (Karlén and Kuylenstierna, 1996) and the Netherlands (Van Geel *et al.*, 1996; 1998) and that of the major ^{14}C anomalies caused by low solar irradiation.

In order to understand better the possible correlation between changes in global climate and changes in solar irradiation, it is now necessary to establish whether minor ^{14}C changes (high and low solar irradiation) in the past were also related to climatic oscillations (Van Geel *et al.*, 1996); whether there was a similar periodicity between climate variations and variations in the atmospheric ^{14}C production rate (Stuiver, 1980); and whether we can

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find improved climate proxy-records for studying the correlation (Eddy, 1977; Stuiver *et al*., 1991).

Properties of peat deposits, such as peat humification, pollen composition, plant macrofossils (Aaby, 1976; Barber *et al*., 1994; Chambers *et al*., 1997), and both the hydrogen and carbon isotopic composition (Schiegl, 1972; Sukumar *et al*., 1993) have been used as proxy indicators of past climate conditions. The $^{13}C/^{12}C$ ratio in mosses and sedges in peat has been considered as a new method for reconstructing atmospheric CO_2 concentration (White *et al*., 1994). Brenninkmeijer *et al*. (1982) suggested that the variations in $\delta^{18}O$ of peat cellulose in some areas can be linked to changes of the regional climate. Recent improvements (Saurer *et al*., 1998; Edwards *et al*., 1994; Brenninkmeijer and Mook, 1981; Thompson and Gray, 1977) in the analytical techniques for measuring oxygen isotope ratios of plant cellulose present opportunities for testing new applications in palaeoenvironmental studies. Here we report for the first time a continuous $\delta^{18}O$ record of peat cellulose covering the past 6000 years and the response of climate variation inferred from the proxy-record to solar forcing, which covers the correlation both between abrupt warming or cooling events and solar activity and between periodicities of climate and solar irradiation.

Jinchuan peat: site, stratigraphy, sample preparation and isotope measurements

The peat bog sampled is located to the west of Jinchuan Town of Huinan County of Jilin Province of China (42° 20′N, 126° 22′E) (Figure 1). The area is more than 100 hectares at an altitude of around 600 m above sea level. It is close to the western Pacific Ocean with a large and fairly constant annual mean relative humidity (70 ± 3%). The peat bog originates from a barrier lake formed by volcanic activity with a relatively stable hydrological condition.

Our previous investigations of the plant remains in 30 cores recovered along three survey lines have shown that the Jinchuan peat mire has a regular distribution of plant species in both horizontal and vertical directions (Chai *et al*., 1990), and has a constant accumulation rate (Sun and Yuan, 1990). For this study, we collected a 6 m long core of undisturbed peat using a portable cutting drill.

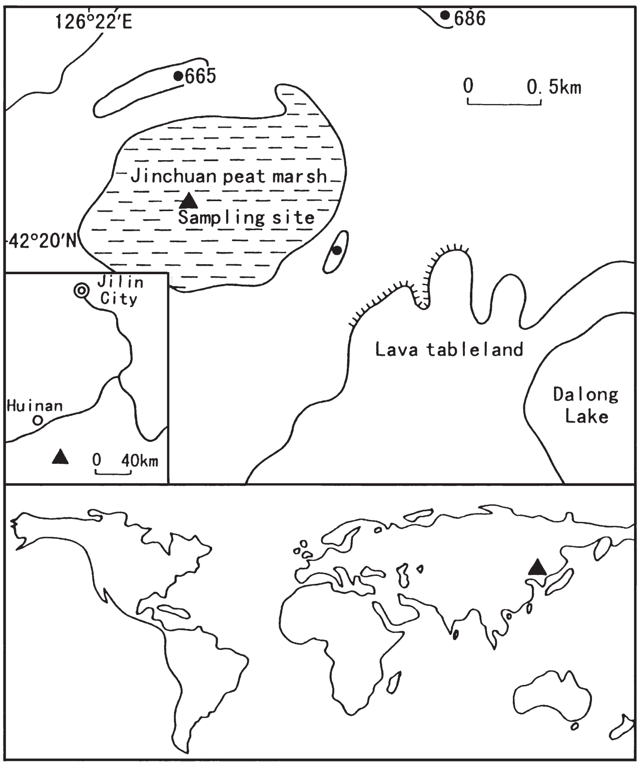


Figure 1 Location of the sampling site (filled triangle) on three different scales.

Figure 2 shows that the *Carex* species, such as *Carex schmidtii* and *C. lasiocarpa*, dominate the plant remains in the whole peat core, except around 5 m depth where plant fragments of Gramineae, mainly reed (*Phragmites communis*) can be distinguished. *Sphagnum* occurs in small amounts. Because of the absolute majority of *Carex* plants and the similar water regimes of the vascular plants which may lead to a smaller scatter of $\delta^{18}O$ values of peat cellulose (Brenninkmeijer *et al*., 1982), we consider that as a first approximation the influence of both those Gramineae and *Sphagnum* plants on the isotopic composition of the peat cellulose is negligible. In addition, in this specific area adjoining to the West Pacific Ocean where the annual mean humidity is relatively constant, the $\delta^{18}O$ values in precipitation generally closely follow the mean annual temperature (Burk and Stuiver, 1976; Dansgaard, 1964). Therefore, the $\delta^{18}O$ of the peat cellulose can be assumed to reflect the surface air temperature because the source water used by the peat plants is predominantly meteoric water from the study area (Epstein *et al*., 1977; Brenninkmeijer *et al*., 1982; Burk and Stuiver, 1976). Hence, the $\delta^{18}O$ of the peat cellulose can be considered qualitatively as a proxy of temperature change. The higher the $\delta^{18}O$ in the peat cellulose, the higher the surface air temperature.

The chronology of the sequence is based on ^{14}C dating of five peat samples collected from the core (Table 1). The ^{14}C dates were calibrated using the computer program CALIB-3 (Stuiver and Reimer, 1993) and with linear interpolation we obtained a time scale in calendar years (Figure 3). The linear relationship (r^2 = 0.994) between the calibrated ^{14}C ages and depth of peat deposits suggests that peat accumulation could be considered as uniform with a rate of about 1.0 mm year^{-1} (Figure 2b), which agrees with earlier work (Sun and Yuan, 1990).

Each sample consisting of a 2 cm thick slice corresponds to about 20 years. Alpha cellulose was prepared by a method based upon the standard sodium chlorite oxidation of lignin and solution of hemicelluloses described by Green (1963) from the samples above 5 m depth only, in order to avoid the portion of apparent change of plant composition (Figure 2a). Oxygen isotope analysis was performed on CO_2 gas produced from cellulose samples, using an improved nickel pyrolysis technique (Edwards *et al*., 1994). Analytical uncertainty for the method is ± 0.3‰.

Surface air temperature variation inferred from $\delta^{18}O$ of peat cellulose

The $\delta^{18}O$ time series of the peat cellulose shows a broad arc shape with $\delta^{18}O$ values ranging from about +15‰ to +22‰ (Figure 3). Three main stages of climate variation during the past 6000 years can be identified for northeastern China. Between about 4000 BC and 2600 BC nearly all of the $\delta^{18}O$ values are lower than the overall mean values of $\delta^{18}O$. We interpret this as a relatively cold period, which coincides with the cold period of the middle Holocene of North America and Europe (Denton and Karlén, 1973). However, within this cold interval rapid climatic fluctuations were also recorded. We suggest that cold climate had some impact on the social development during this period. Indeed, archaeological investigations (Shi *et al*., 1992) showed that the number of sites of culture remains corresponding to the late Yangshao Culture is clearly smaller than that before or after in both the Yellow River and the Yangtze River basins.

Since about 2600 BC the $\delta^{18}O$ of the peat cellulose increases

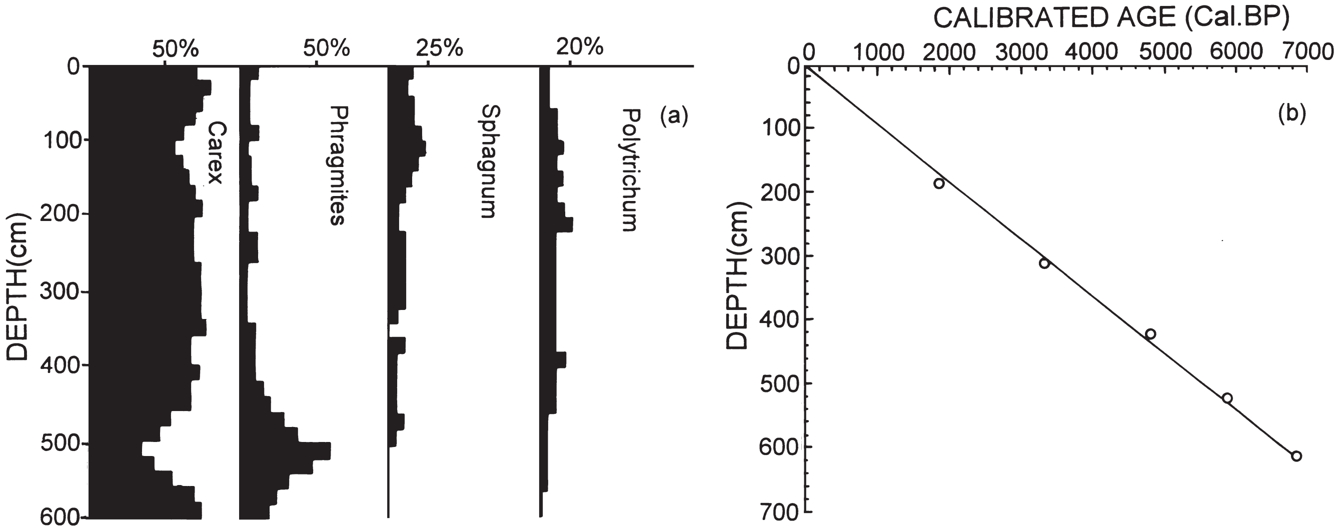


Figure 2 (a) Downcore variations (estimated volumes) of main plant remains, and (b) an age-depth plot for the Jinchuan peat.

Table 1 Ages for peat samples from Jinchuan

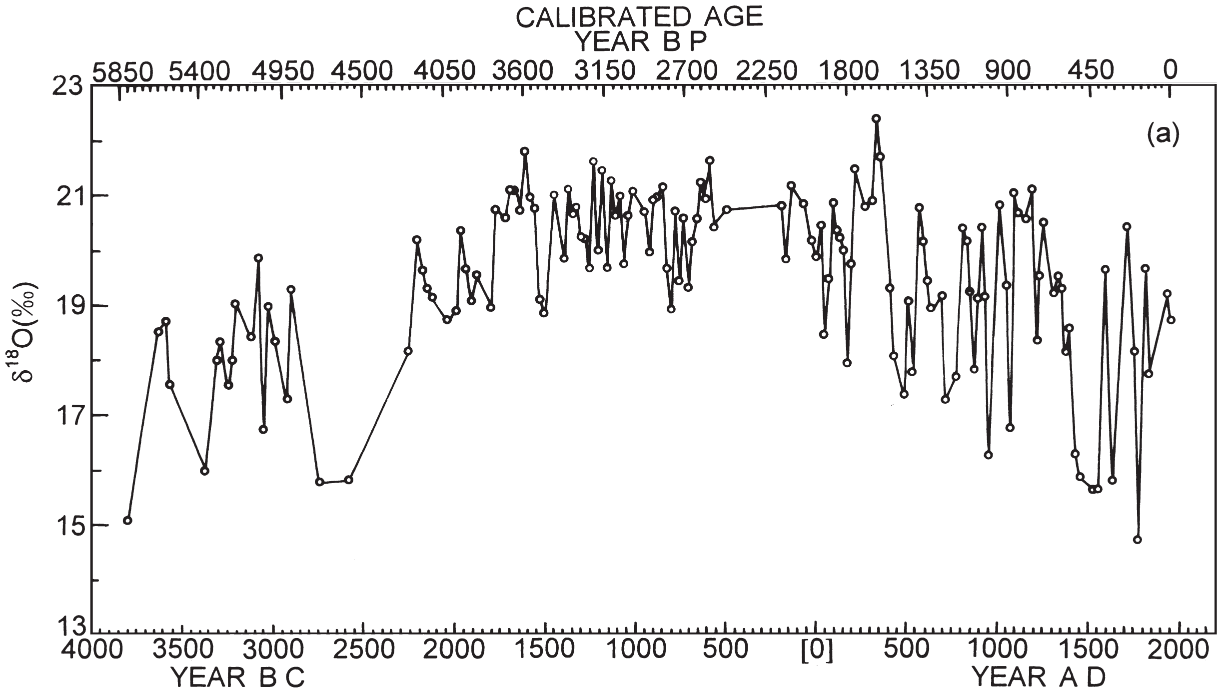
Depth (cm)	^{14}C age (± s.d.) (yr BP)	Calibrated age ranges (cal. yr BP)		Calibrated age (cal. yr BP)	Calibrated age ranges (cal. yr BC/AD)		Calibrated age (cal. yr BC/AD)
		1σ	2σ		1σ	2σ	
185–190	1945 ± 70	1949–1817	2014–1712	1880	AD 1–133	AD 64–238	AD 75
310–315	3120 ± 95	3450–3431 3406–3213	3548–3515 3480–3069	3350	BC 1500–1481 1456–1263	BC 1598–1565 1530–1119	1400 BC
420–425	4275 ± 115	4972–4934 4878–4812 4762–4691 4677–4647	5251–5184 5127–5115 5059–4520	4840	BC 3022–2984 2928–2862 2812–2741 2727–2697	BC 3301–3234 3177–3165 3109–2570	2890 BC
520–525	5130 ± 160	6164–6154 6086–6075 6032–6003 5999–5714	6281–5583	5910	BC 4214–4204 4136–4125 4082–4053 4049–3764	BC 4331–3633	3960 BC
610–615	6020 ± 130	7014–6729	7199–6542	6870	BC 5064–4779	BC 5249–4592	4920 BC

Visible plant debris was removed from the peat samples. One sample from the upper layer did not have sufficient carbon for accurate dating after removal of visible modern rootlet. Radiocarbon dating of the samples was carried out at the National Laboratory of Loess and Quaternary Geology in Xi'an of China by the method described by Head *et al.* (1989). The samples were treated, using acid, base, and acid, in order to remove calcareous material and younger humid matter. The pretreated samples were prepared as liquid benzene, and dated by low-level liquid scintillation counting (Wallac Quantulus 1220). The carbon mass of a dated sample is 200 mg, and counting lasted 3000 min. All ^{14}C ages are based on the half-life of 5568 ± 30 years. The reference year for BP is AD 1950. The radiocarbon ages have been produced using the computer program CALIB-3 (Stuiver and Reimer, 1993). The least-squares fit is: Y = 0.0893*X (r^2 = 0.9939), where Y is the depth in cm and X is the calibrated age in cal. yr BP.

continuously and reaches its maximum at about 1600 BC, corresponding to a total increase of 6‰ within 1000 years. This coincides with the continuous increase of $\delta^{18}O$ in the Greenland Summit ice core for the same period (Ice Core Working Group, 1998) and is clearly a natural warming process with both the largest amplitude and the longest duration in the past 6000 years recorded by the peat $\delta^{18}O$. We note that it was about during this period when the ancient civilizations in central China rapidly developed in the two great river basins (Shi *et al.*, 1992). By this time, ancient China had completed its transition from the Neolithic to Bronze Age and had created the first characters on bones or tortoise shells, one of the oldest scripts in the world and precursor to the contemporary Chinese character set. We concur with earlier archaeological studies that these rapid social developments may be partly attributed to the climate conditions being favourable for ancient agriculture. Based on the records of more than 100 000 pieces of oracle inscriptions discovered in the Yin Xu, the capital of the Shang Dynasty (about 1600–1000 BC) of ancient China, archaeologists have shown that the climate of the Shang Dynasty was clearly warmer than that of today (Chu, 1926; 1931; 1973; Wittfogel, 1940).

The warm climate continued until about AD 350, lasting for nearly 2000 years, covering eight dynasties in Chinese history. There has been abundant archaeological and historical material recording the generally warm condition at the time (Chu, 1973). However, the peat $\delta^{18}O$ record also reveals some climatic deviation to cool conditions, for example, at about 1500 BC, and particularly in the period of 800–700 BC. The climate shift from warm to cool condition about 800 BC on both hemispheres has been documented in several studies (Van Geel *et al.*, 1996; 1998). Our results provide new evidence for this global cold event, although the magnitude of the temperature drop inferred from the peat $\delta^{18}O$ record seems to be smaller.

During the period from about AD 350 to 500 the $\delta^{18}O$ of the peat cellulose indicates a clear drop in temperature. This period corresponds to the Northern and Southern Dynasties (about AD 380–589) in Chinese history. It has been noticed that the climate in this period was so cold that lakes and rivers nearby Jianye, the



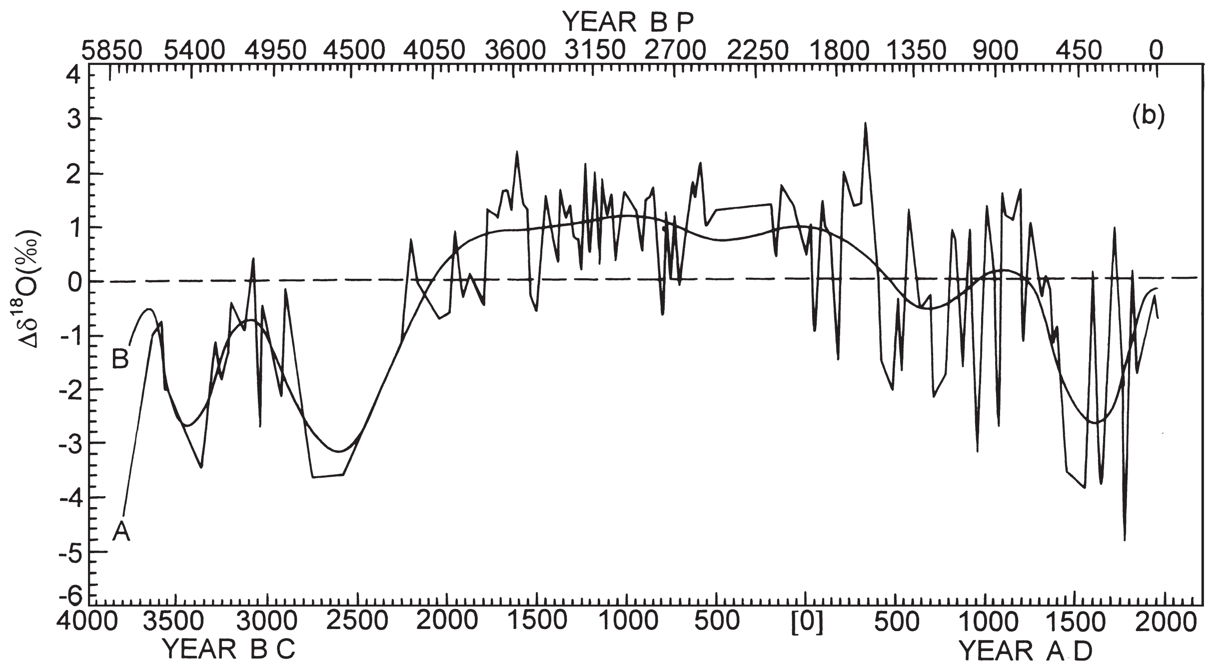


Figure 3 (a) The $\delta^{18}O$ profile of peat cellulose for the Jinchuan core. (b) Curve A is the same as in (a) but expressed as $\Delta\delta^{18}O$. The zero line indicates the mean of the peat cellulose $\delta^{18}O$ values for the entire profile. The timescale is based on calibrated radiocarbon dates given in Table 1. Positive shifts denote higher (than average) air temperature and negative shifts lower air temperature. Curve B shows the long-term trend of the $\Delta\delta^{18}O$ variation which is fitted with a 15-order polynomial function.

capital of the Southern Dynasty (it is Nanjing of Jiangsu Province today), were frozen in the winter season. The nobility of the Southern Dynasty were able to build a large icehouse for preserving food. It has been estimated that the mean winter temperature and the annual mean temperature at that time were 2°C and 1°C lower than at present respectively (Chu, 1973). From then on the climate of NE China shows strong fluctuations and gradually moves towards the 'Little Ice Age' although some episodes of warm climate occurred.

In the period from about AD 500 to 1800, nine minima are recorded in the $\delta^{18}O$ curve. Three minima of $\delta^{18}O$ at about AD 1550, 1650 and 1750 correspond with the most severe cold climate, which occurred between AD 1550 and 1700 (Lamb, 1966). There is an obvious warm period represented by the high $\delta^{18}O$ from around AD 1100 to 1200 which may correspond to the Medieval Warm Epoch of Europe (Lamb, 1966). At that time, the northern boundary of the cultivation of citrus tree (*Citrus reticulata* Blanco) and *Boehmeria nivea* (a perennial herb), both subtropical and thermophilous plants, moved gradually into the northern part of China, and it has been estimated that the annual mean temperature was 0.9–1.0°C higher than at present (Zhang, 1994).

Response of climate to solar forcing

The above results allow us to make a comparison between climate variation inferred from $\delta^{18}O$ of peat cellulose and solar activity derived from the tree-ring $\Delta^{14}C$ data on a decadal timescale over the last 6000 years. As can been seen in Figure 4 there is a remarkable, nearly one to one, correspondence between the changes of atmospheric $\Delta^{14}C$ and the variation in $\delta^{18}O$ of the peat cellulose despite a lack of $\delta^{18}O$ data in some periods, for example, at Nos 24, 25, 26, 41 and 42 (Figure 4), due to insufficient peat cellulose samples at those periods for accurate oxygen isotope measurements. Around 22 warm periods labelled by even numbers, including the well-known 'Medieval Warm Period' (No. 8), correspond to around 22 maxima of solar activity labelled by even numbers. Around 22 cool periods, covering the well-known 'Little Ice Age' (No. 5), correspond to around 22 minima of solar activity labelled by odd numbers. When an apparent change of solar activity extends for more than about 100 years, the peat record often responds: for example, groups of $\delta^{18}O$ maximum values at Nos 8, 22, 32 and 36 solar changes, and groups of $\delta^{18}O$ minimum values at Nos 5, 13, 15, 27, 37 and 53 solar changes. In general, the larger the excursions of the $\Delta^{14}C$ from its long-term trend the clearer the corresponding variations of the peat $\delta^{18}O$; for instance, the apparently large excursions of $\Delta^{14}C$ at Nos 55, 53, 51, 45, 41 and 5 corresponding to the relatively cold periods and the 'Little Ice Age'. One obvious exception, however, is the strongest ^{14}C peak at around 800 BC (No. 27), which does not show up strongly in the $\delta^{18}O$ data as noted earlier. The cause of this discrepancy is unclear and needs further investigation. During the cold periods around before 2600 BC and after AD 1200, the amplitude of the peat $\delta^{18}O$ variations is larger than during the intervening warm period, which seems to be also generally the case for the atmospheric $\Delta^{14}C$ record of tree-rings, with two exceptions (Nos 27 and 25).

To examine further the possible sun-climate relationship, we have performed spectral analysis on the peat $\delta^{18}O$ time-series. The Scargle method for non-equispaced data (Scargle, 1982) was applied and smoothed using a binomial filter to remove the long-term trend. As shown in Figure 5, one of the important features is the clear higher-frequency oscillation in climate variation. The strong cyclic signals of about 86 years and possibly 93 years are most likely to be related to the sunspot cycle known as the Gleissberg cycle, which is supported by aurora evidence. The similar periodicities, such as 88, 85 and 82 years, have been also detected in the spectral analysis on atmospheric ^{14}C production rate record (Stuiver *et al.*, 1991; Stuiver and Braziunas, 1993).

The comparison between the periodicities of the peat $\delta^{18}O$ and atmospheric ^{14}C production rate shows that the lower-frequency cycles detected in the peat isotope time series, such as about 101, 110, 127, 132, 140, 155, 207, 245, 311, 590, 820 and 1046 years, are very similar with the cycles of solar activities characterized by radiocarbon in tree-rings (Stuiver *et al.*, 1991) although there are differences in their relative spectral density. The most prominent cycles of the peat isotope time-series are 132, 127, 111, 140 and 93 years. This is the first time that so many different cyclic signals of the climate variation have been simultaneously found in a peat $\delta^{18}O$ record extending over the past several millennia in a mid-latitude region. These periodicities clearly show that the climatic variability is complex, but its response to changes in solar forcing is sensitive.

Furthermore, the fluctuation trends of the peat $\delta^{18}O$ curve shows a complex model of climate variation; i.e., the 6000 years peat $\delta^{18}O$ time-series contains five small quasi-sinusoidal

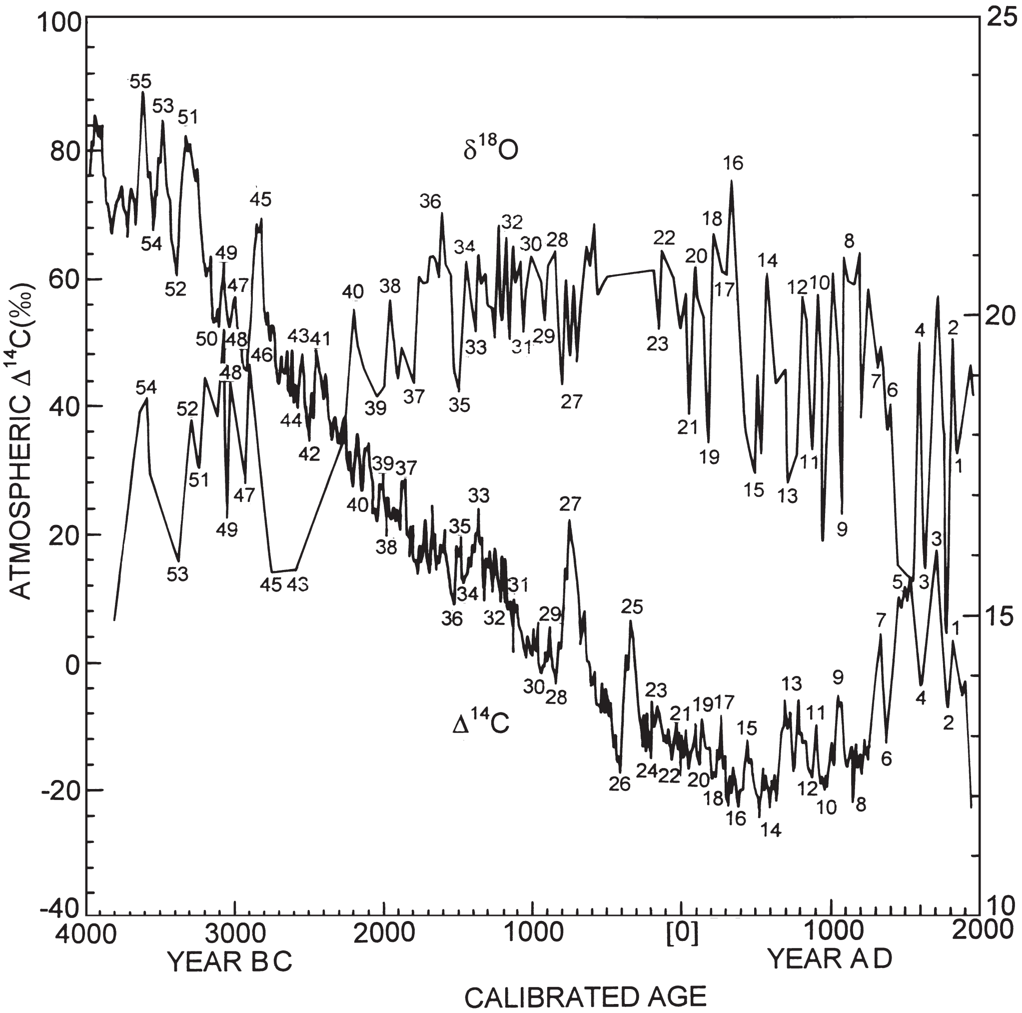


Figure 4 A comparison between $\delta^{18}O$ of peat cellulose (this study) and $\Delta^{14}C$ of the tree-rings (Stuiver and Reimer, 1993) plotted against the same timescale.

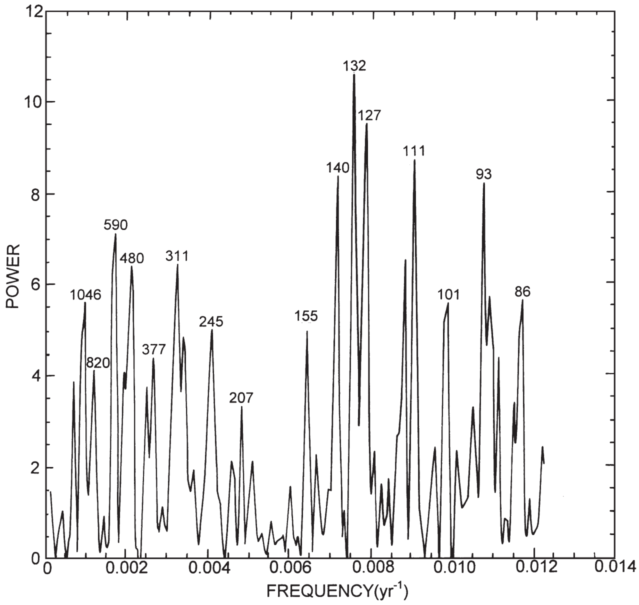


Figure 5 Power spectrum of the δ^{18}O time-series of peat cellulose from Jinchuan after removing long-term trend. Numbers above peaks indicate the corresponding periodicities (years).

fluctuations superimposed on a possibly large sine-wave (curve B in Figure 3b). The mean cycle of the five quasi-sinusoidal fluctuations is about 1000 years. It agrees with the period of around 1046 years in the spectral analysis (Figure 5), and also with the period of roughly 1000 years covering the Maunder Minimum and the Medieval Maximum of solar variation deduced by Eddy (1976). However, detailed work is needed for trying to make a comparison between the complex model of climate variation and the radiocarbon record of tree-rings on the 1000-year timescale.

On the δ^{18}O-based climate record (curve B in Figure 3b), two abrupt warming intervals are particularly interesting. There was a clear warming between about 2600 BC and 1600 BC. Solar forcing may have played an important role because this period coincides with a series of stronger solar activity maxima (Nos 44, 42, 40 and 36 in Figure 4) following an era with four strong solar activity minima (Nos 55, 53, 51 and 45 in Figure 4). The second abrupt warming took place between about AD 1600 and AD 1950. This may be also attributed to the increase of solar activity since the seventeenth century in addition to the influence of volcanic and human activities (Eddy, 1976; Lean *et al.*, 1995).

If the trend after AD 1950 continues as shown in Figure 3b, the next maximum of the peat δ^{18}O would be expected between about AD 2000 and AD 2050. This solar activity forced warming would be a natural background of century-scale climate variability to be taken into account when we try to assess the anthropogenic contribution to the climate variability.

Conclusions

(1) The history of the climate variation over the past 6000 years in northeastern China has been reconstructed by combining a 20-year resolution δ^{18}O proxy-record of peat plant cellulose with Chinese historical and archaeological data. The results show that during the past 6000 years the climate variation inferred from δ^{18}O of peat varied from relatively cold, to warm and back to cold. In every stage, however, the climate has shown several abrupt variations that coincide with the climate information recorded in Chinese archaeological and historical data, and also with climate variation worldwide. The amplitude of the climate variations in the cold periods seems to be larger than those in the warm periods.

(2) On timescales of decades to centuries, the abrupt climate variations, including around 22 warming and 22 cooling events, and a series of periodicities, are strikingly correlative to the changes of solar irradiation and solar periodicities. This correlation reveals that the climate variability in the past 6000 years is likely to be forced mainly by solar variability.

(3) The climate warming since about AD 1600 inferred from δ^{18}O of peat cellulose is one portion of the long-term fluctuations of the climatic system apparently modulated by solar forcing. This would be a natural background of century-scale climate variability to be taken into account when we try to assess the contribution of anthropogenic climate change to the natural climate variability.

(4) The δ^{18}O time-series of Jinchuan peat cellulose is a sensitive high-resolution proxy climate record. During the past several decades a number of advantages of peat deposits, for instance, the widespread distribution, the deep deposition which is found spanning over 10 000 years, the convenience for sampling and preservation, and the possibility for extracting and comparing many kinds of climate proxy indicators, has been revealed. The isotopic record from peat cellulose has great potential for the investigation of climate change and climate forcing during the Holocene.

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