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Evidence for solar forcing of climate variation from δ ^{18}O of peat cellulose

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Abstract There have been a number of investigations for examining the possible link between long-term climate variability and solar activity. A continuous δ^{18}O record of peat cellulose covering the past 6 000 years and the response of climate variation inferred from the proxy record to solar forcing are reported. Results show that during the past 5 000 years the abrupt climate variations, including 17 warming and 17 cooling, and a serious of periodicities, such as 86, 101, 110, 127, 132, 140, 155, 207, 245, 311, 820 and 1 050 years, are strikingly correlative to the changes of solar irradiation and periodicity. These observations are considered as further evidence for a close relationship between solar activity and climate variations on time scales of decades to centuries.

Keywords: solar variability, climatic change, peat, δ ^{18}O, radiocarbon anomalies.

There have been a number of investigations for examining the possible link between long-term climate variability and solar activity. The history of solar variability can be derived from the ^{14}C content in tree-rings[1,2]. Based on the historical records and fossil radiocarbon in tree rings, Eddy inferred eighteen apparent long-term changes in the level of solar activity during the past 7 500 years. He suggested that in every case when long-term solar activity falls, mid-latitude glaciers advance and climate cools, at the time of high solar activity glaciers receding and climate warming[3,4]. Wigley and Kelly 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 compared climatic records from both hemispheres with ^{14}C anomalies and found a significant correlation[5]. More recent investigations on proglacial lacustrine sediments and alpine-glacial moraines as well as plant composition of the raised-bog show a good correspondence between the timing of the past major cold events in Scandinavia[6] and the Netherlands[7] and that of the major ^{14}C anomalies (low solar irradiation).

In order to better understand the possible correlation between changes in global climate and changes in solar irradiation it is now necessary to know whether minor ^{14}C changes (high solar irradiation) in the past were also related to climatic oscillations[7], whether there was a similar periodicity between climate variations and variations in atmospheric ^{14}C[2,4], and whether we can find improved climate proxy records of studying the correlation[4].

Properties of peat deposits such as peat humification, pollen composition, plant macrofossil[8−10], and both hydrogen and carbon isotopic composition[11,12] have been used as proxy indicators of the past climate conditions. An early study[13] 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[13−15] 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 6 000 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 and solar activity and between periodicities of climate and solar irradiation.

1 Region and method

The peat researched is located to the west of Jinchuan Town of Huinan County, Jilin Province, China (42° 20′ N, 126° 22′ E) (fig. 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 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 thirty 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[16], and has a constant accumulation rate[17]. In this study we collected a 6-m long core of undisturbed peat using a portable cutting drill.

The *Carex* species, such as *Carex schmidtii* and *lasiocarpa*, dominate the plant remains in the whole core except around 5 m depth where plant fragments of *Grammineae*, mainly reed (*Phragmites communis*) can be distinguished. *Sphagnum* of non-vascular plants 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[13], we consider that as a first approximation the influence of both those *Grammineae* 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[18,19].

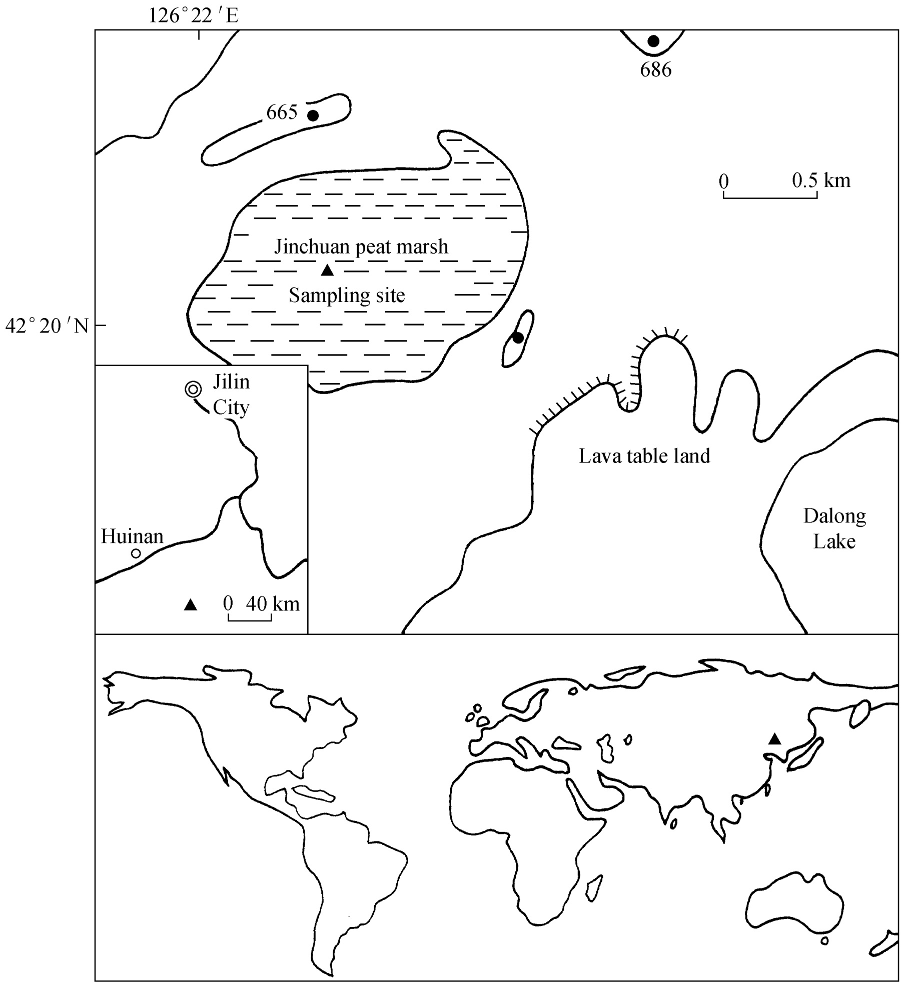

Fig. 1. Map showing the location of the sampling site (filled triangle) in the global and China. On the inset map the filled triangle shows relative position of the sampling site with Jilin City of Jilin Province. Filled cycles are given in meters above mean sea level.

Therefore, the δ^{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 predominately meteoric water from the study area[20,13,18]. Hence the δ^{18}O of the peat cellulose can be considered qualitatively as a proxy of temperature change. The higher the δ^{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 apparent linear relationship between the ^{14}C ages of peat deposits and depth suggests that peat accumulation was uniform at a rate of about 1.0 mm/a, which agrees with earlier work[17]. The ^{14}C dates were calibrated[22], and with linear interpolation we obtained a time scale in calendar years.

Table 1 Ages for peat samples from Jinchuan

Depth/cm	^{14}C age (±s.d.)/a BP	Calibrated age/a BP	Calibrated age/a
185—190	1 945±70	1 885	65 (AD)
310—315	3 120±95	3 375	1410(BC)
420—425	4 275±115	4 860	2910(BC)
520—525	5 130±160	5 930	3965(BC)
610—615	6 020±130	6 890	4940(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.[21] 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 3 000 min. All ^{14}C ages based on the half-life of 5 568±30 years. The calibrated ages are mean ages based on dendrochronological data[22]. The reference year for BP is AD 1950. The least-squares fit is Y=9.597*X+152(r=0.999 7), where Y is the ^{14}C age in year and X the depth in cm.

Each sample consisting of a 2-cm thick slice corresponds to about 20 years. Alpha cellulose was prepared by the method described by Green[23] from the samples above 5 m depth in order to avoid the portion of apparent change of plant composition. Oxygen isotope analysis was performed on CO_2 gas produced from purified cellulose samples, using an improved nickel pyrolysis technique[14]. Analytical uncertainty is ±0.3‰. Fig. 2 shows the δ^{18}O profile of peat cellulose for the Jinchuan core.

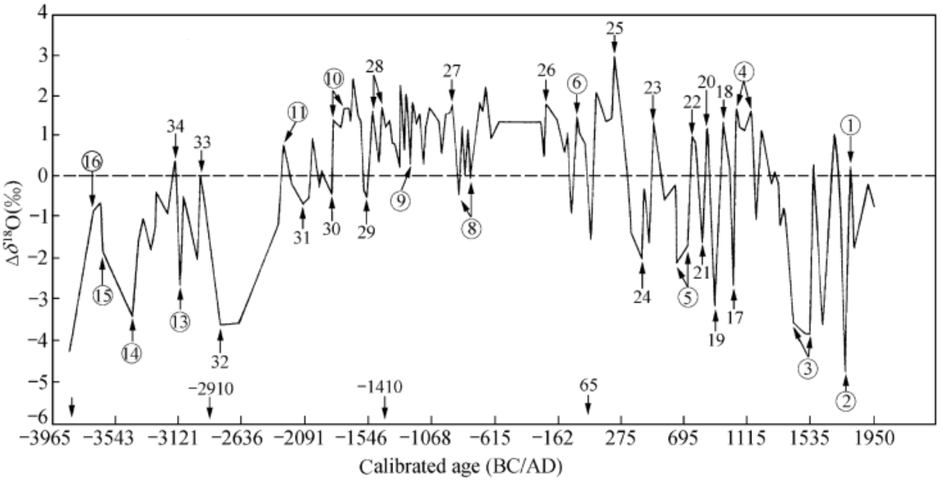

Fig. 2. The δ^{18}O profile of peat cellulose for the Jinchuan core. The zero line indicates the mean of the peat cellulose δ^{18}O values for the entire profile. The negative numbers on the time scale denote BC. The numbers of the apparent solar excursions suggested in previous studies are marked on the $\Delta\delta^{18}$O curve; the circled numbers (①—⑯) refer to features described by Eddy[4], and the rest by Wigley and Kelly[5], Stuiver and Reimer[24] respectively.

2 Response of climate to solar forcing

The characterization of variability in solar irradiation has been considered as one element in efforts to understand climate change. The history of solar change can be provided by the record of atmospheric ^{14}C content derived from tree-ring measurements of ^{14}C. Based on historical records and fossil radiocarbon in tree-rings Eddy suggested eighteen apparent longer-term changes in the level of solar activity in the past 7 500 years, of which sixteen were within the past 6 000 years. In fig. 2, the major solar excursions identified previously[4,5,24] are marked on the peat $\Delta\delta^{18}O$ record. We can find that there is a remarkable, nearly one-to-one, correspondence between the apparent changes of solar activity and the variation in the $\delta^{18}O$ of the peat cellulose despite a lack of $\delta^{18}O$ data at No.7 and No.12 due to insufficient peat cellulose samples at those periods for accurate oxygen isotope measurements (see also table 2). 17 maximums of solar activity correspond to around 17 warm periods, and 17 minimums of solar activity correspond to around 17 cool periods. When an apparent change of solar activity extends for more than 100 years, the peat record can often give a group of $\delta^{18}O$ data, for example, a group of $\delta^{18}O$ maximum values at No.4, No.10 and No.11 solar changes, and a group of $\delta^{8}O$ minimum values at No. 5, No. 8 and No. 9 solar changes respectively. In general, the larger the excursions of the radiocarbon content from its long-term trend, the clearer the corresponding variations of the peat $\delta^{18}O$.

One obvious exception, however, is the strongest ^{14}C peak at around 800 BC (No. 8), which does not show up very strongly in the $\delta^{18}O$ data. The climate shift from warm to cool condition in about 800 BC (850—760 BC) on both hemispheres has been documented in several studies[7]. 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. The period of around 800 BC happens to be Western Zhou Dynasty (around 1027—771 BC) in Chinese history. According to a historical account of that freeze occurring in the Han River, a big tributary of the Yangtze River, in 897 BC it may imply that the climate at that time turned cold on one occasion[25].

During the cold periods before 2000 BC and after 1000 AD the amplitude of the peat $\delta^{18}O$ variations seems to be larger than during the warm period in between, which is also generally the case for the radiocarbon record of tree-rings with two exceptions (No. 7 and No. 8).

To further examine the possible sun-climate relationship, we have performed spectral analysis on the peat $\delta^{18}O$ time series. We applied the method of Scargle for non-equispaced data[26] and smoothed the $\delta^{18}O$ data using a binomial filter to remove the long-term trend. As shown in fig. 3, 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 solar activity known as the Gleissberg cycle which is supported by aurora evidence. The other low-frequency cycles detected in peat isotope time series (fig. 3), such as about 101, 110, 127, 132, 140, 155, 207, 245, 311, 480, 590, 820 and 1 046 years, all coincide with the cycles of solar activities characterized by radiocarbon in tree-rings[2], and with the cycles of climatic variation indicated by other types of proxy records respectively[6,8−10]. This is the first time that so many different cyclic signals of the climate variation have been found in a peat $\delta^{18}O$ record extending over past several millennia. These periodicities clearly show that the climatic variability is considerably complex but its response to changes in solar forcing is sensitive.

Table 2 Major solar excursions in the past 6 000 years and the climate-proxy record of peat δ^{18}O

	Feature	Beginning and ending radiocarbon record				^{14}C anomaly	Peat δ ^{18}O record	
		from Eddy[4]		based on Stuiver & Reimer[24] b)		from Wigley & Kelly[5]	sense	date
1a)	maximum	AD1800	—	AD1800	—		maximum	AD1811
2	maximum	AD1660	AD1770	AD1654	AD1714	AD1690	minimum	AD1745
3	minimum	AD1420	AD1570	AD1416	AD1534	AD1510	minimum	AD1514－1535
4	maximum	AD1140	AD1340	AD1130	AD1250		maximum	AD1048－1150
5	minimum	AD660	AD770	AD700	AD790	AD730	minimum	AD653－720
6	maximum	AD1	AD140	AD50	AD180		maximum	AD31
7	minimum	420BC	300BC	400BC	250BC	330BC	minimum	—
8	minimum	800BC	580BC	800BC	600BC	730BC	minimum	810－778BC
9	minimum	1400BC	1200BC	1300BC	1220BC	1350BC	minimum	1295BC
10	maximum	1850BC	1700BC	1820BC	1700BC		maximum	1846－1753BC
11	maximum	2350BC	2000BC	2200BC	2100BC		maximum	2282BC
12	maximum	2700BC	2550BC	2700BC	2600BC		maximum	—
13	minimum	3200BC	3050BC	3100BC	3000BC	3290BC	minimum	3120BC
14	minimum	3410BC	3270BC	3400BC	3200BC	—	minimum	3416BC
15	minimum	3670BC	3410BC	3600BC	3400BC	3590BC	minimum	3606BC
16	maximum	4220BC	3700BC	3700BC	3620BC		maximum	3695BC
17	minimum			AD1020	AD1100	AD1050	minimum	AD1030
18	maximum			AD950	AD1000		maximum	AD951
19	minimum			AD900	AD950		minimum	AD905
20	maximum			AD820	AD900		maximum	AD863
21	minimum			AD800	AD820		minimum	AD822
22	maximum			AD770	AD800		maximum	AD754
23	maximum			AD480	AD650		maximum	AD485
24	minimum			AD400	AD500		minimum	AD418
25	maximum			AD200	AD300		maximum	AD250
26	maximum			240BC	150BC		maximum	234BC
27	maximum			920BC	850BC		maximum	914BC
28	maximum			1450BC	1400BC		maximum	1441BC
29	minimum			1510BC	1450BC		minimum	1557BC
30	minimum			1850BC	1820BC		minimum	1873BC
31	minimum			2100BC	2050BC		minimum	2091BC
32	minimum			2810BC	2200BC	2830BC	minimum	2805BC
33	maximum			3000BC	2810BC		maximum	2973BC
34	maximum			3150BC	3050BC		maximum	3142BC

a) Numbers from 1 to 34 correspond to the number in fig. 2. b) The beginning and ending dates are measured against the fossil radiocarbon record presented by Stuiver and Reimer[24].

Furthermore, the modeling analysis of fluctuation trend of the peat δ^{18}O curve shows a complex model of climate variation that the 6 000-year peat δ^{18}O time series contains four small quasi-sinusoidal fluctuations superimposed on a possibly large sine wave. The mean cycle of the four quasi-sinusoidal fluctuations is about 1 000 years, which agrees with the period of around 1 046 years in the spectral analysis mentioned above and also with the period of roughly 1 000-year covering the Maunder Minimum and the Medieval Maximum of solar variation deduced by Eddy[4]. More detailed work is needed for trying to make a comparison between the complex models of the long-term climate variation inferred from peat δ^{18}O and solar activity derived from the radiocarbon of tree-rings.

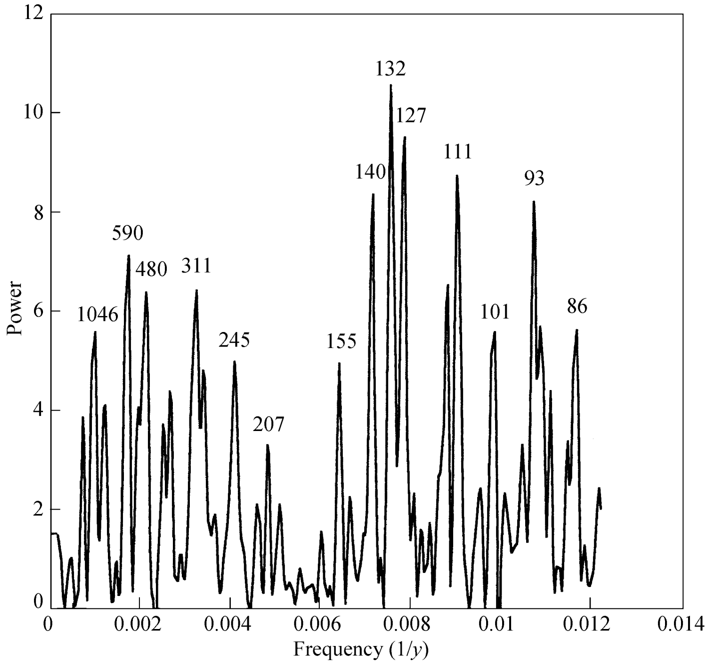

Fig. 3. Power spectrum of the δ^{18}O time series of peat cellulose from Jinchuan. Numbers above peaks indicate the corresponding periodicities (years).

3 Conclusion

The history of the climate variation in the past 6 000 years in Northeast China has been reconstructed. On time scales of decades to centuries the abrupt climate variations, including 17 warming and 17 cooling, and a series of periodicities are strikingly correlative to the changes of solar irradiation and periodicity. This correlation clearly reveals that the climate variability in the past 6 000 years is most likely to be forced mainly by solar variability.

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