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Temperature responses to quasi-100-yr solar variability during the past 6000 years based on $\delta^{18}\text{O}$ of peat cellulose in Hongyuan, eastern Qinghai–Tibet plateau, China

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Abstract

During the past 6000 years, the temperature variation trend inferred from $\delta^{18}\text{O}$ of peat cellulose in a peat core from Hongyuan (eastern Qinghai–Tibet plateau, southwestern China) is similar to the atmospheric ^{14}C concentration trend and the modeled solar output trend. The general trend of Hongyuan $\delta^{18}\text{O}$ during the past millennium also coincides well with the atmospheric ^{14}C concentration trend, the ^{10}Be concentration trend in an ice core from the South Pole, the reconstructed total solar irradiance trend, as well as the modeled solar output trend. In addition, temperature events also correspond well to solar perturbations during the past 6000 years. Therefore, the driving force of Holocene temperature variations should be properly ascribed to solar activity. The spectrum analysis further illustrates that quasi-100-yr fluctuation of solar activity was probably responsible for temperature variations in northeast Qinghai–Tibet plateau during the past 6000 years.

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Keywords: Peat; Oxygen isotopic composition; Temperature; Solar activity; Qinghai–Tibet plateau; China

1. Introduction

A Considerable number of investigations have been performed to study Holocene temperature variations and the related mechanisms in China recently (Hong et al., 2000; Xu et al., 2002; Yang et al., 2002). Temperature changes inferred from $\delta^{18}\text{O}$ in peat cellulose at Hongyuan (Xu et al., 2002) and Jinchuan (Hong et al., 2000) (Fig. 1) are synchronous with

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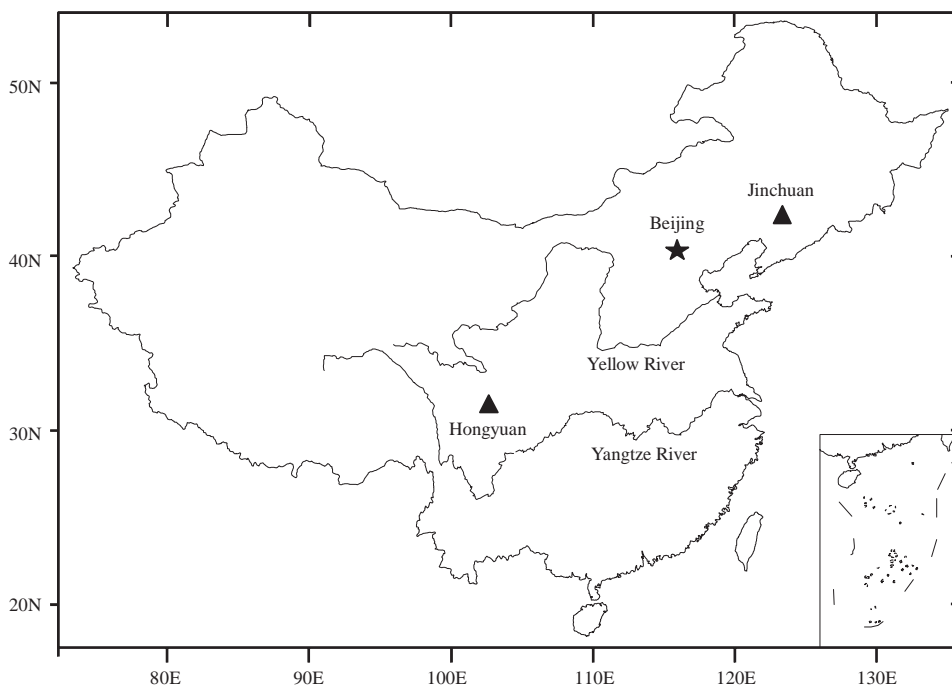


Fig. 1. Locations of Hongyuan peat profile (32°46' N, 102°30' E) (Xu et al., 2002) and Jinchuan peat profile (42°20' N, 126°22' E) (Hong et al., 2000). Hongyuan and Jinchuan are about 2400 km apart.

those discovered in numerous studies in China and those revealed by other studies in the Northern Hemisphere (Xu et al., 2002). Recently, Yang et al. (2002) studied temperatures in China over the past 2000 years and discovered that temperature trends in different regions of China are consistent with one another.

Close attention should be paid to the synchrony of temperature variations in different regions in China because the climate dynamics are quite variable. China is one of the most active and extensive monsoon regions. Different regions, influenced variably by a number of monsoon sources, have different climatic patterns. The complex topography can also lead to climatic variations (An, 2000). Thus, if the temperatures in different regions are synchronous, a common and dominant forcing process is strongly supported. The nature of such a common forcing agent is still debated.

Variation of the total energy reaching the Earth may be a major factor that influences the Earth's climates. During the latest two sunspot cycles, Earth-satellite measurements indicate that the total solar

output, which has long been considered constant, has varied by 0.1% (Reid, 1997). These small solar perturbations, whose effect can be magnified by different feedback mechanisms (Van Geel et al., 1999; Bond et al., 2001; Shindell et al., 2001), may ultimately lead to climatic oscillations on several time scales, such as annual to decadal and/or centennial scales, as well as millennial scales. Therefore, solar variability can possibly be considered as a primary factor when studying the mechanisms of Holocene temperature variations (Blackford and Chambers, 1995; Chambers et al., 1999; Van Geel et al., 1999; Reid, 1997; Lean and Rind, 1999; Beer et al., 2000).

The atmospheric ^{14}C concentration has long been recognized as a sensitive proxy of solar variability (Eddy, 1976). In addition, variations of the modeled solar output (Perry and Hsu, 2000), which are consistent with temperatures, may also be used as a surrogate of solar activity. In this paper, we compare temperature variations inferred from $\delta^{18}\text{O}$ in peat cellulose at Hongyuan with solar activity inferred from several kinds of solar proxy indices, and perform

cross-spectral analysis to investigate the relationship between temperatures and solar variability. Our study reveals that quasi-100-yr fluctuations of solar activity are possibly the primary driving force of Chinese temperatures during the past 6000 years.

2. Background and method

The sampling site of the Hongyuan peat profile is located in the west of the Hongyuan County, north-west Sichuan province, eastern Qinghai–Tibet plateau (Fig. 1), with an elevation of 3466 m above sea level. Climate in Hongyuan is cool to cold, belonging to the continental plateau monsoon climate type. Mean annual relative humidity is relatively constant ($70 \pm 3\%$). Mean annual amount of precipitation (650 mm) varies mildly, and is sufficient for the growth of grass. However, temperature varies remarkably revealed both from the meteorological records and from the ice-core temperature archives (Yao et al., 2000). The meteorological records indicate that mean annual lowest temperature varies between -8.0 – -2.4 °C, mean annual temperature varies between 0.5 – 4.0 °C, and mean annual highest temperature varies between 8.5 – 12.1 °C. Temperatures recorded in $\delta^{18}\text{O}$ of ice cores reveal that temperatures in Qinghai–Tibet plateau vary much more sharply than those in eastern China at low altitude (Yao et al., 2000).

Climatic signals can be well registered into the oxygen/hydrogen isotopic signals of precipitation during the condensation process of vapor to precipitation (Dansgaard, 1964; Rozanski et al., 1992). Since mean annual relative humidity and mean annual amount of precipitation vary mildly, and temperature varies sharply, the $\delta^{18}\text{O}$ of precipitation can be generally considered to reflect the mean annual air temperature around our study site (Dansgaard, 1964; Rozanski et al., 1992). This has been verified by a strong positive correlation between contemporaneous measurements of $\delta^{18}\text{O}$ in precipitation and air temperature from an array of meteorological stations over the northern part of Tibet plateau (Yao et al., 1996). The long-term $\delta^{18}\text{O}$ record in Dunde ice core (Yao and Thompson, 1992), Malan ice cap (Wang et al., 2003), Guliya ice cap (Yao et al., 2000), and Rongbuk ice core (Kang et al., 2001) over Qinghai–Tibet plateau also reflected air tempera-

ture sensitively. A quantitative relation between $\delta^{18}\text{O}$ of Guliya ice cap and temperatures has been estimated by Yao et al. (2000): $\delta^{18}\text{O}(\text{‰})=0.67$, $T=-13.59$ °C, $R^2=0.69$. The gradient of variation of $\delta^{18}\text{O}$ in precipitation is about $0.67\text{‰}/\text{°C}$ (Yao et al., 2000).

For plants using precipitation as source water, the isotopic signals of precipitation can be modulated and recorded into plant cellulose through series of plant physiological processes (Dongmann et al., 1974; Yakir and DeNiro, 1990; Flanagan et al., 1991; Roden et al., 2000). Since both the relative humidity and the amount of precipitation vary mildly, the oxygen/hydrogen isotopic fractionations during the plant physiological processes should be relatively constant (Dongmann et al., 1974; Yakir and DeNiro, 1990; Flanagan et al., 1991; Roden et al., 2000). Therefore, the variation of $\delta^{18}\text{O}$ in plant cellulose should mainly reflect that of the precipitation (Gray and Thompson, 1976; Burk and Stuiver, 1981; Breninkmeijer et al., 1982; Roden et al., 2000; Anderson et al., 2002; Waterhouse et al., 2002). Because source water of the grass in the studying peat land is predominantly meteoric water, the $\delta^{18}\text{O}$ of peat cellulose should be quantitatively correlated to that of the precipitation, and thereby to air temperature.

An undisturbed peat core of 4.95 m in depth was sampled. Specimens were prepared as slices every one cm thick. Investigation of plant species of the peat profile using microscopy makes clear that several different species (mostly C3 plant) remain in the peat profile and no C4 plant has been identified. *Carex mulieensis* is the most predominant species in the whole profile. Although variable species of plant has variable isotopic compositions in the peat profile, our previous study (Hong et al., 2003) revealed that the time series of the $\delta^{13}\text{C}$ of mono-species cellulose (*C. mulieensis*) correlate well with that of the bulk peat cellulose. We also found that $\delta^{13}\text{C}$ of the bulk peat cellulose has less noise-signals compared with that of the mono-species cellulose, and should be more reliable to reflect the climate changes in relatively long-term timescales (Hong et al., 2001, 2003). Similarly, Hemming et al. (1998) found that stable isotopes of the mixture of several trees are more sensitive to climate changes than those of single trees. Therefore, we concern more about the $\delta^{18}\text{O}$ of the bulk peat cellulose than that of mono-species cellulose in this study.

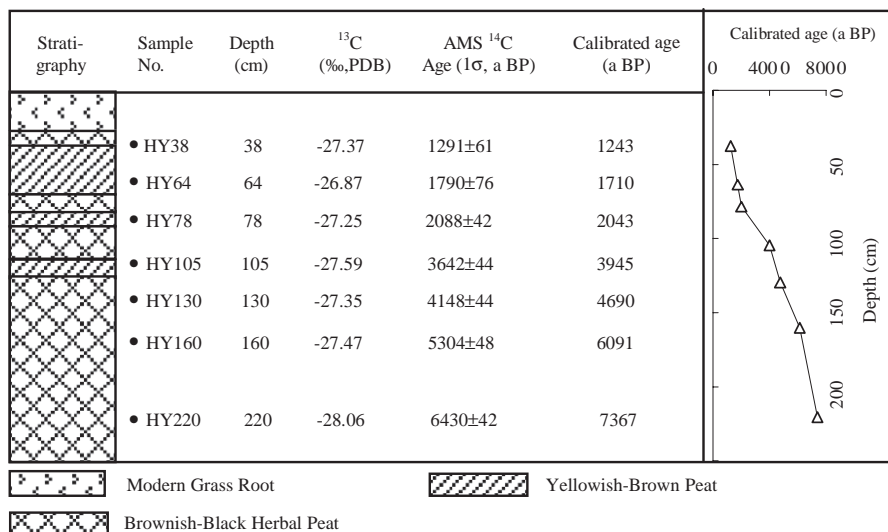


Fig. 2. Hongyuan peat profile and radiocarbon dating. Radiocarbon dating was performed using bulk cellulose on the accelerating mass spectrometer at NIES of Japan (Kume et al., 1997) and the ^{14}C ages were calibrated with *Calib4.3* (Stuiver and Reimer, 1993). The whole profile in 1995 is 495 cm in depth and has a time span of about 11,800 years. Data presented in this study are the ages of the upper 250 cm layer. The time series are obtained by linear interpolation, and all dates described in this study are calibrated radio carbon ages.

Alpha-cellulose was extracted from peat samples using the standard Jimmy–Wise method (Yapp and Epstein, 1982). Radiocarbon dating was performed using bulk peat cellulose, and the ^{14}C ages were calibrated with CALIB 4.3 (Stuiver and Reimer, 1993). Dates of the samples are obtained by linear

interpolation (Fig. 2). Oxygen isotopic composition was measured using the improved nickel tube pyrolysis technique (Edwards et al., 1994), with an experimental error less than $\pm 0.2\%$. As interpreted above, $\delta^{18}\text{O}$ of peat cellulose and the differences to the mean value ($\Delta\delta^{18}\text{O}$) can be regarded as mea-

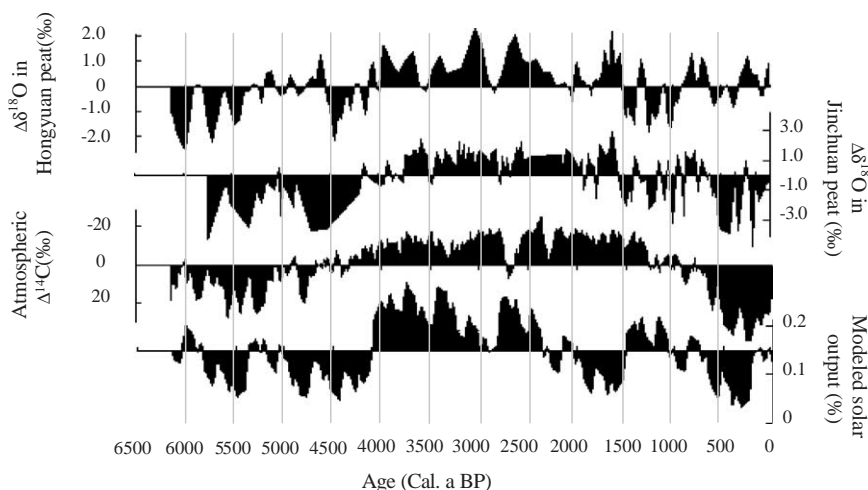


Fig. 3. Comparison of general trends between temperature and solar activity during the past 6000 years. The $\delta^{18}\text{O}$ series are from Xu et al. (2002) for Jinchuan. The atmospheric ^{14}C series is from Stuiver and Reimer (1993) after removal of linear trend. The modeled solar output series is from Perry and Hsu (2000). The $\delta^{18}\text{O}$ of peat cellulose and the differences to the mean value ($\Delta\delta^{18}\text{O}$) are measured of the temperature variations and are subsequently referred to as such. Higher $\delta^{18}\text{O}$ in peat cellulose corresponds to higher temperature, and vice versa (see the text for details).

tures of temperature variations and are subsequently referred to as such.

3. Comparisons of general trends between temperature and solar activity

The trends of temperature variation for both Hongyuan and Jinchuan are similar to the trends of solar activity during the past 6000 years (Fig. 3). In general, temperature varied at a low level from 6000 to 4200 a BP, corresponding to low solar activity. Temperature varied at a high level from 4200 to 1500 a BP, corresponding to high solar activity. Then, temperature fell to a relatively low level from 1500 a BP to present, consistent with low solar activity.

A more detailed comparison between temperature and solar activity during the last millennium is presented in Fig. 4, including the Hongyuan $\delta^{18}\text{O}$ series, atmospheric ^{14}C concentration (Stuiver and Reimer, 1993), ^{10}Be concentration in an ice core from South Pole (Steig et al., 1998), the total solar irradiance reconstructed by Bard et al. (2000), and the modeled solar output (Perry and Hsu, 2000). It is interesting that the coherence between trends of solar activity and temperature exists on centennial scales (see the 5th-

order polynomial fits in Fig. 4), but not on decadal/interdecadal scales (Fig. 4). This may suggest an important issue that, on interannual to interdecadal scales, the climatic dynamics of different regions may be quite variable. Recent studies reveal that temperatures inferred from $\delta^{18}\text{O}$ of Malan ice core in northern Qinghai–Tibet plateau (Wang et al., 2003) and temperatures inferred from tree-ring widths around the Hongyuan region (Xu et al., submitted for publication) response well to the North Atlantic Oscillations and the ENSO, implying that the atmospheric circulations play important roles on modulating temperatures on interannual to interdecadal scales over the northern Qinghai–Tibet plateau.

4. Solar activity, temperature, and cultural responses

Palaeoclimate studies and records of human activity and migration reveal that, during the past 4000 years, there were four striking world-wide cooling events possibly related to solar activity, occurring near 4000, 2750, 1550, and 350 a BP (Xu, 1998). These four cooling events can be detected from $\delta^{18}\text{O}$ series in peat cellulose at Hon-

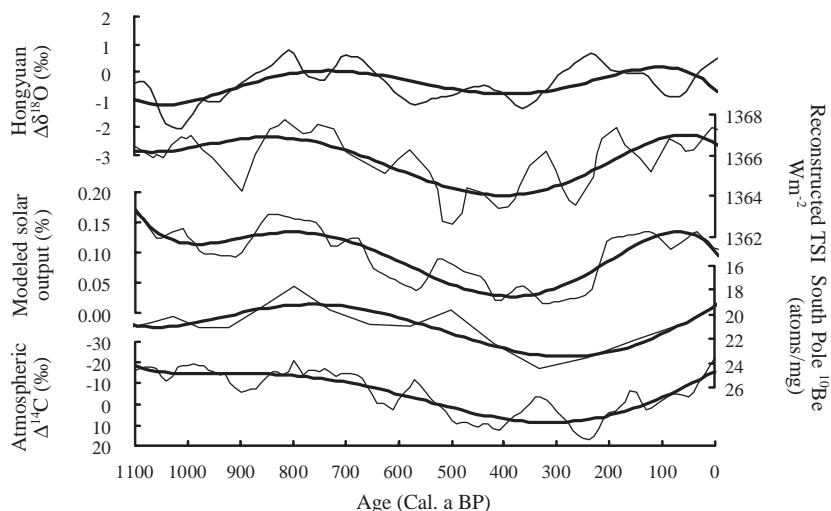


Fig. 4. Comparison of general trends between temperature and solar activity during the last millennium. The atmospheric ^{14}C series is from Stuiver and Reimer (1993) (after removal of linear trend). The modeled solar output series is from Perry and Hsu (2000). The reconstructed TSI (total solar irradiance) series is from Bard et al. (2000). The ^{10}Be series is from Steig et al. (1998). Thin lines indicate the data series. Thick lines represent 5th-order polynomial fits of each series.

gyuan and Jinchuan (Fig. 5). More recently, Bond et al. (2001) identified eight IRD (ice-rafted debris) events associated with cooling climate in the North Atlantic region. These IRD events also correlate well with the atmospheric ^{14}C concentrations and the marine ^{10}Be concentrations, suggesting, again, that solar activity is a primary driving force of climatic variations in the Holocene (Bond et al., 2001). Such IRD cold events occurred four times (see the numbers from 1 to 4 in Fig. 5) during the past 6000 years.

Other historical and human activity records support a relation between temperature changes and variations in solar activity (Weiss et al., 1993; DeMenocal, 2001; Hodell et al., 2001). In the Sahara, nearly all of the freshwater lakes desiccated, and the ancient Saharan civilizations collapsed, about 4600–4000 a BP (Xu, 1998). Cold climates may have forced the Mesopotamians to abandon their settlements in northern Mesopotamia, and the Akkadian Empire in south Mesopotamia collapsed (Weiss et al., 1993). The ancient civilizations in the Indus River region and in Egypt also collapsed. To escape the cold climates, the Indo-Europeans moved to Greece, south Russia, Persia, India, and northwest China (Xu, 1998).

Climates varied on a more favorable level during the interval from 4200 to 1500 a BP, corresponding to

a time of relatively strong solar activity (Fig. 3). Chinese civilization developed rapidly during this warm period. The birth of the ancient Chinese civilization has been assumed to take place about 4000 a BP (Xu et al., 2002). Ancient China witnessed a transition from the Neolithic Age to the Bronze Age and the creation of one of the oldest written languages (Hong et al., 2000). More than 100,000 pieces of oracle inscription have been discovered in Yin Xu, capital of the Shang Dynasty (3350–2950 a BP). Descriptions on those oracles reveal relatively warm conditions during this period. Europeans moved northwards into Scandinavia and engaged in agriculture. The Assyrian Empire, the Hittite Empire, China (Shang Dynasty), and Egypt prospered at that time (Xu, 1998).

A decrease in temperature occurred during 2900–2700 a BP both in Hongyuan and Jinchuan. The ancient book Bamboo recorded that during the periods of 857–853, 828, 803, 780 BC, there was a prevailing cold and dry climate (Xu et al., 2002). Many rivers, especially the Jing, the Wei, and the Luo ceased to flow. The cold-dry condition lasted nearly 77 years. This event was named the “King-Li Drought and Rivers Desiccating Event” (Xu et al., 2002). This cold event, documented as having a worldwide distribution (Van Geel et al., 1996), coincided with a remarkable

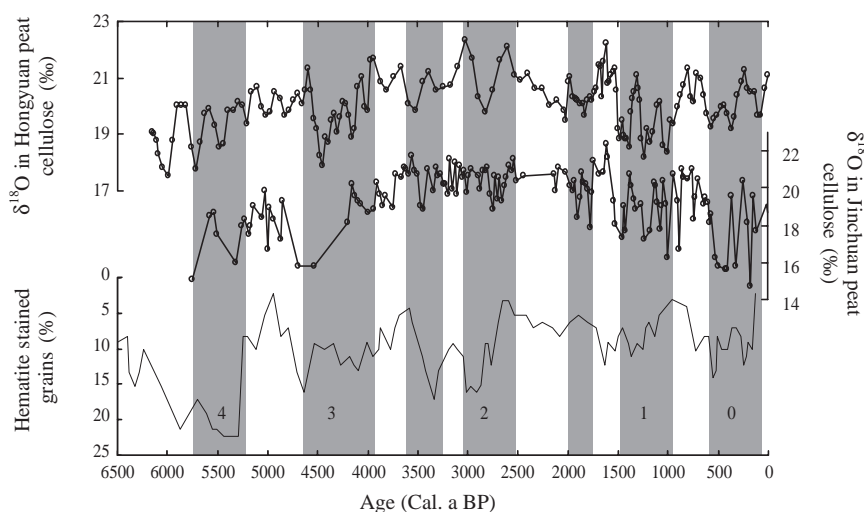


Fig. 5. Comparison of temperature variations in China and IRD events in North Atlantic. The Hematite stained grains series is from Bond et al. (2001). Numbers from 1 to 4 represent the IRD events identified by Bond et al. Number 0 indicates the Little Ice Age.

decrease in solar activity about 2700 a BP inferred from the atmospheric ^{14}C series (Stuiver and Reimer, 1993).

As illustrated in Figs. 3 and 5, it was cold between AD 1250 and 1850, corresponding to the Little Ice Age. Considerable evidence suggests that cold climate during the Little Ice Age was related to solar activity (Lean and Rind, 1999; Shindell et al., 2001). The low temperatures at both Hongyuan and Jinchuan during this time were likely induced by changes in solar activity.

5. Correlations between temperature and solar activity

Cross-spectrum analysis was applied to explore possible correlations between the Hongyuan $\delta^{18}\text{O}$ series and the atmospheric ^{14}C series, and between the Hongyuan and Jinchuan $\delta^{18}\text{O}$ series. Significant 82, 107, and 122-yr periodicities exist in the cross spectra between Hongyuan temperatures and solar activity (Fig. 6A). Similar cross periodicities of 92 and 112-yr exist between Hongyuan and Jinchuan temperatures (Fig. 6B). Those periodicities are ap-

proximately similar with the periodicities of 79, 88, and 123–127-yr for the Hongyuan $\delta^{18}\text{O}$ series (Fig. 7A), the periodicities of 83, 96, and 113-yr for the Jinchuan $\delta^{18}\text{O}$ series (Fig. 7B), and the periodicities of 88 and 148-yr for atmospheric ^{14}C concentrations (Fig. 7C). This kind of periodicities, near a 100-yr band, has been linked to solar activity by recent studies (Yu and Ito, 1999; Castagnoli et al., 2002; Domack et al., 2001; Dean et al., 2002), suggesting that temperature variations on those scales in Hongyuan and Jinchuan are induced by solar activity.

Quasi-1650, 450, and 260-yr periodicities exist in the cross-spectra between Hongyuan $\delta^{18}\text{O}$ and the atmospheric ^{14}C series (Fig. 6A), as well as in cross-spectra between the Hongyuan and Jinchuan $\delta^{18}\text{O}$ series (Fig. 6B). Similar significant periodicities of 420 and 218-yr have been detected in the atmospheric ^{14}C series (Stuiver and Braziunas, 1989) and a 1450-yr periodicity can also be extracted in the band pass component of the ^{14}C series (Mayewski et al., 1997). However, these periodicities are not so strong (as compared with the quasi-100-yr periodicities) in the power spectrums of Hongyuan (Fig. 7A) and Jinchuan $\delta^{18}\text{O}$ (Fig. 7B), suggesting that energy fluc-

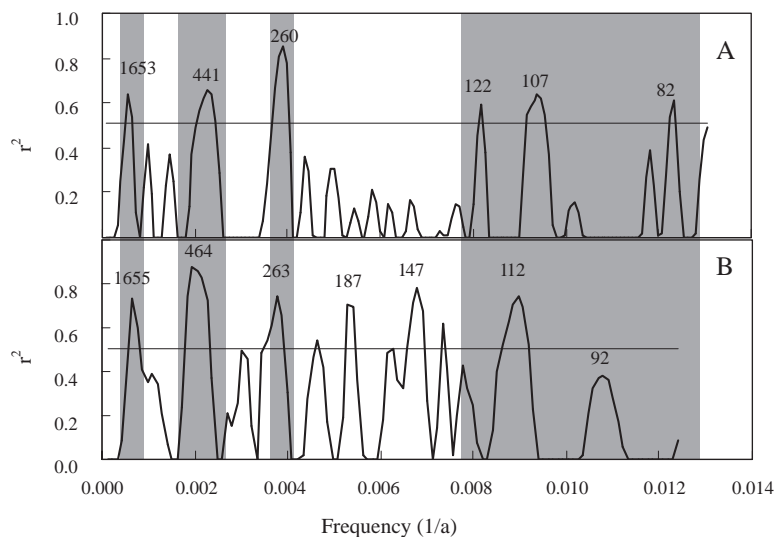


Fig. 6. Cross spectrum analyses for Hongyuan $\delta^{18}\text{O}$ series–the atmospheric ^{14}C series (A), and for Hongyuan–Jinchuan $\delta^{18}\text{O}$ series (B). Vertical axis indicates the square of correlated coefficients. Numbers represent the cross periodicities. Horizontal dotted thin lines represent significant levels of 80%. Cross spectrum analysis was performed using the software SPECTRUM (Schulz and Stettger, 1997). Parameters of the software in this study are: OFAC=5; HIFAC=1; $N_{\text{seg}}=4$; Welch-window; $\alpha=0.2$ (see Schulz and Stettger (1997) for details).

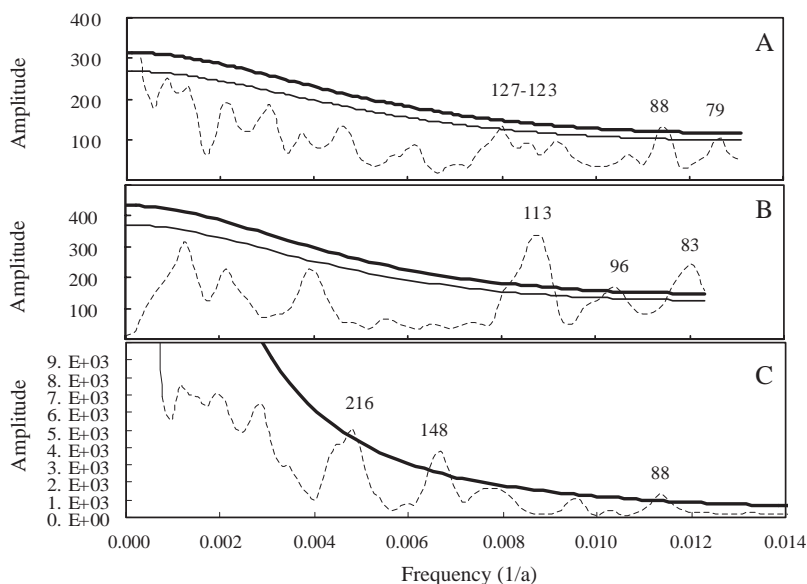


Fig. 7. Power spectrum analysis for Hongyuan $\delta^{18}\text{O}$ (A), Jinchuan $\delta^{18}\text{O}$ (B), and atmospheric ^{14}C concentrations (C). Numbers indicate the significant periodicities. Thin lines indicate 90% significant level and thick lines indicate 95% significant level. Power spectrum analysis was performed using Redfit 35 (Schulz and Mudelsee, 2002). Parameters of the software in this study are: nsim=1000, mctest=T, rho_{pre}=−99.0, ofac=2, n50=4, iwin=1 (see Schulz and Mudelsee (2002) for details).

tuations on these scales are not the primary factor that influences regional temperatures in China during the past 6000 years.

6. Conclusions

During the past 6000 years, temperature variations in China exhibit high synchrony among different regions, and importantly, are in-phase with those discovered in other regions in the northern hemisphere. Comparisons between temperature variations and solar activities indicate that both temperature trends on centennial/millennial timescales and climatic events are related to solar variability, suggesting that solar variability is possibly a primary driving force that influences temperatures. Cross-spectrum analyses indicate that there exists a series of periodicities between temperatures in Hongyuan, temperatures in Jinchuan, and solar activities. These common periodicities are mainly a response to variations in solar activity. Quasi-100-yr fluctuations of solar activity may be the primary driving force of temperature during the past 6000 years in China.

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