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Climatic oscillations over the past 120 kyr recorded in the Guliya ice core, China

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Abstract

Recently, several ice cores were drilled on the Tibetan Plateau to examine climate and environmental changes. Based on the temperature proxy records in the Guliya ice core, climate oscillations over the past 120 kyr were examined using wavelet analysis and singular spectrum analysis methods. The results showed two main Milankovitch-type oscillatory modes, 22 and 44 kyr. The 22 kyr period corresponds to the precession period and 44 kyr period corresponds to the Earth axis's obliquity inclination period. The two periods combined explain ~43% of the variance. In addition, there are millennial and 10 thousand years time scales periods, which may be related to the Dansgaard–Oeschger (D–O) cycles and the Heinrich (H) events.

1. Introduction

The ice core records from Antarctica and Greenland provide very useful proxy archives for paleoclimate study (Lorius et al., 1985; Johnsen et al., 1992; Chappellez et al., 1993; Dansgaard et al., 1993; Greenland Ice Core Project (GRIP) Members, 1993; Grootes et al., 1993). Recently, an additional ice core with a length of 3270.2 m was recovered in Antarctica, the preliminary results of which show that the time scale extends back to ~950 kyr (EPICA community members, 2004). Ice cores from Antarctica and Greenland record a series of important climate events that have occurred on a global scale (Blunier et al., 1988). Thus, one of the challenges is to explain the linkages between these long ice core records. To this end, it would be very important to examine the high-resolution and long-term climate records from mid to low latitudes.

Over the last 20 yr, several ice cores were drilled on the Tibetan Plateau in order to examine local and regional climatic and environmental changes (Thompson et al., 1989, 1990, 1995, 1997, 2000; Thompson, 1992; Yao et al., 1990, 1995a, b, 1996, 1997). The record from the Guliya ice core (309 m), drilled on the western side of the Plateau, extends back over 120 kyr. Yao et al. (1997) examined climatic variations in this ice core record since the Last Interglacial. In this paper, the climatic oscillations recorded in the Guliya ice core, as well as their relationships with the solar radiation variations, are investigated further using wavelet analysis and singular spectrum analysis (SSA) methods. In addition, sub-orbital climatic oscillations that also occur in the record are also discussed.

2. Guliya ice core and analytical methods

The Qinghai–Tibetan (Q–T) Plateau in China, with an average altitude of over 4500 m, is considered to be especially sensitive to the anticipated global warming (Hansen and Lebedeff, 1987). Ice cores drilled from several places on the Plateau (Yao et al., 1995a, 2002) have been used to reconstruct climatic changes. Guliya (35°17′N,

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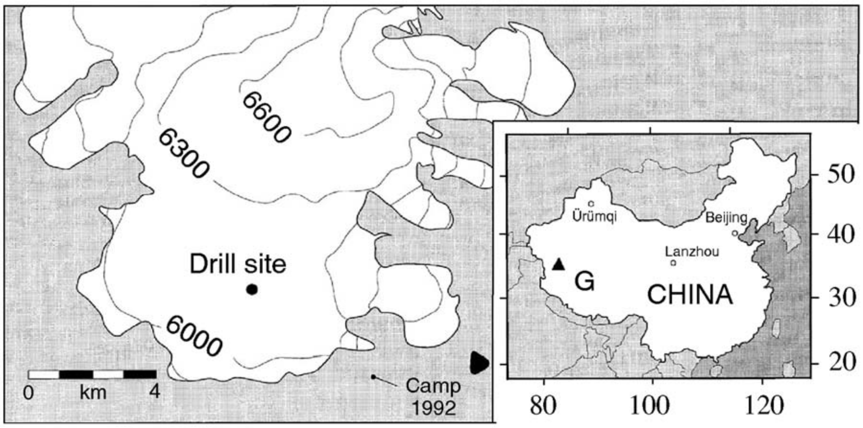

Fig. 1. Locations of the Guliya (G) ice cap and the site where the 308.6 m Guliya ice core was drilled. Drill site elevation is 6200 m above sea level (after Thompson et al., 1997).

81°29′E) in the western Kunlun Mountains (Thompson et al., 1995) is the deepest polar-type ice cap in central Asia, with an area of 376 km^2 (Yao et al., 1997). Three ice cores with respective lengths of 308.7, 93.2 and 34.5 m were drilled successfully at elevations ranging from 6200–6700 m asl. The longest ice core was drilled (Fig. 1) using an electromechanical corer from a dry borehole to 200 m and a thermal corer with an alcohol–water mixture from 200 m to bedrock (308.6 m). Ice temperatures were -15.6, -5.9 and -2.1 °C corresponding to depths of 10, 200 and 308.6 m, respectively. Visible horizontal dust layers appeared throughout the core; however, no stratigraphic hiatus was detected.

Thompson et al. (1995, 1997) and Yao et al. (1996) provide detailed descriptions of the field (specifically mass balance measurements) and laboratory (i.e. stable isotope analysis) methods used in the climatic and environmental studies of the Guliya ice core. The mass balance was measured by three methods: (1) accumulation stakes, (2) visible stratigraphy in pits, and (3) insoluble particulate β and tritium horizons (Thompson et al., 1995). Such measurements made in 1990 and 1991 indicate that the ice cap receives ~200 mm w.e. (water equivalent) of accumulation per year (Thompson et al., 1997; Yao et al., 1997), which is used as an estimate of the regional precipitation. Yao et al. (1996) indicated that the net accumulation is closely correlated to the actual precipitation. The variations in oxygen isotopic ratios (δ^{18}O) in the Guliya ice core record have been used as proxies for historical temperature changes on the Q–T Plateau. There is strong evidence that there is a positive relationship between δ^{18}O and temperature in this region (Yao et al., 1995a; Yao et al., 1996).

A powerful method for analyzing localized intermittent oscillations is the wavelet transform (WT) (Holschneider, 1995), which is becoming a common tool in the study of localized power variations within a time series. Important aspects of nonlinear oscillations in a complex system with multiple time scales, such as the climate system, are their modulation in amplitude, phase and frequency. By decomposing a time series into time–frequency space, one is able to determine both the dominant modes of variability and how those modes vary in time. The wavelet transform has been used for numerous studies in geophysics, including tropical convection (Weng and Lau, 1994), El Niño–Southern Oscillation (Gu and Philander, 1995; Wang and Wang, 1996), atmospheric cold fronts (Gamage and Blumen, 1993), the dispersion of ocean waves (Meyers et al., 1993), wave growth and breaking (Liu, 1994) and coherent structures in turbulent flows (Farge, 1992). A complete description of geophysical applications can be found in Foufoula-Georgiou and Kumar (1995), while a theoretical treatment of wavelet analysis is provided by Daubechies (1992). In our analysis, we use the wavelet method introduced by Torrence and Compo (1998).

SSA is based on the idea of sliding a window down a time series and looking for patterns that account for a high proportion of the variance in the views of the series thus obtained (Allen and Smith, 1996). SSA is closely related to the standard meteorological technique of empirical orthogonal function analysis.

3. Wavelet and SSA analysis results

In the middle of the 19th century, James Croll (1875) demonstrated that the timing of the Pleistocene ice ages was related to the periods of Earth's orbit. His theory was modified and developed by Mulitin Milankovitch (1941), a Yugoslavian mathematician. The Milankovitch theory demonstrated that changes of Earth's orbital geometry cause the periodical variations in the insolation distribution, which is thought to be the primary cause of the Pleistocene ice ages. There are three parameters related to the Earth orbital geometry shape: the inclination of the axis, precession and orbital eccentricity. During the Holocene, the precession period is within 19–23 kyr and axis inclination period is within 41–54 kyr (Berger, 1989; Berger and Loutre, 1991). However, calculations show that due to slow changes in Earth's rotation velocity and orbital eccentricity, as well as the changes in the distance between Earth and its moon, the length and intensity of the orbital periods decreased backwards through time; conversely, the periods of precession and inclination are increasing towards the present (Berger, 1984). This is because of the shortening of the distance between Earth and the Moon and the day length. Such changes show the strongest impact on the inclination period.

3.1. Relationship between climate records in Guliya ice core and Earth orbital parameters

Fig. 2 shows the $\delta^{18}O$ record, the real part of its wavelet analysis, and the power spectrum for the past 120 kyr recorded in the Guliya ice core. Two periods are evident: one at 44 kyr, corresponding to the Earth axis's inclination, and the other at 22 kyr, corresponding to the precessional cycle. There is an increasing trend in the precessional periodicity over the past 120 kyr. A 13 kyr signal can also be seen in Fig. 2.

The SSA also demonstrates that the 44 and 22 kyr periods were significant during the past 120 kyr in the Guliya ice core records. The 22 kyr period explains ~25% of the variance while the 44 kyr period accounts for ~18% of the variance. Together they explain ~43% of the variance (Fig. 3). The combination of the two results in the cyclicity that is characteristic of the Glacial stage and Interglacial stages.

Figs. 4(a) and (b) show the similarity in the variations of the precession and the precession component recorded in the Guliya ice core, respectively. However, the variation of the precession component in Guliya ice core lags behind that of the precession. Likewise, Figs. 4(c) and (d) show the inclination variation and the inclination component in the Guliya ice core, respectively, which also vary similarly and have the same lagging relationship. The comparison of the combined curve of the precession and inclination period components with the insolation at 65°N (Fig. 3) strongly indicates that over the past 120 kyr the orbital-scale climatic variations recorded in the Guliya ice core are controlled mainly by variations in insolation.

3.2. Climate oscillation in sub-orbital time scale recorded in the Guliya ice core

The Younger Dryas event, as recorded in the Greenland ice core records, lasted about 1.2 kyr. If the Younger Dryas is only a cooling event, the discovery of the Heinrich events (hereafter abbreviated as H event) reinforced the knowledge of climate instability. The Heinrich events represent the dominant abrupt climate changes on sub-orbital time scales. Heinrich (1998) first suggested the existence of such events, which he noticed in the stratigraphy of a marine core from the northeast Atlantic. He hypothesized that the large icebergs had been discharged from the Glacial ice sheets and melted into the North Atlantic six times during the Last Glacial cycle, and resulted in sedimentary layers

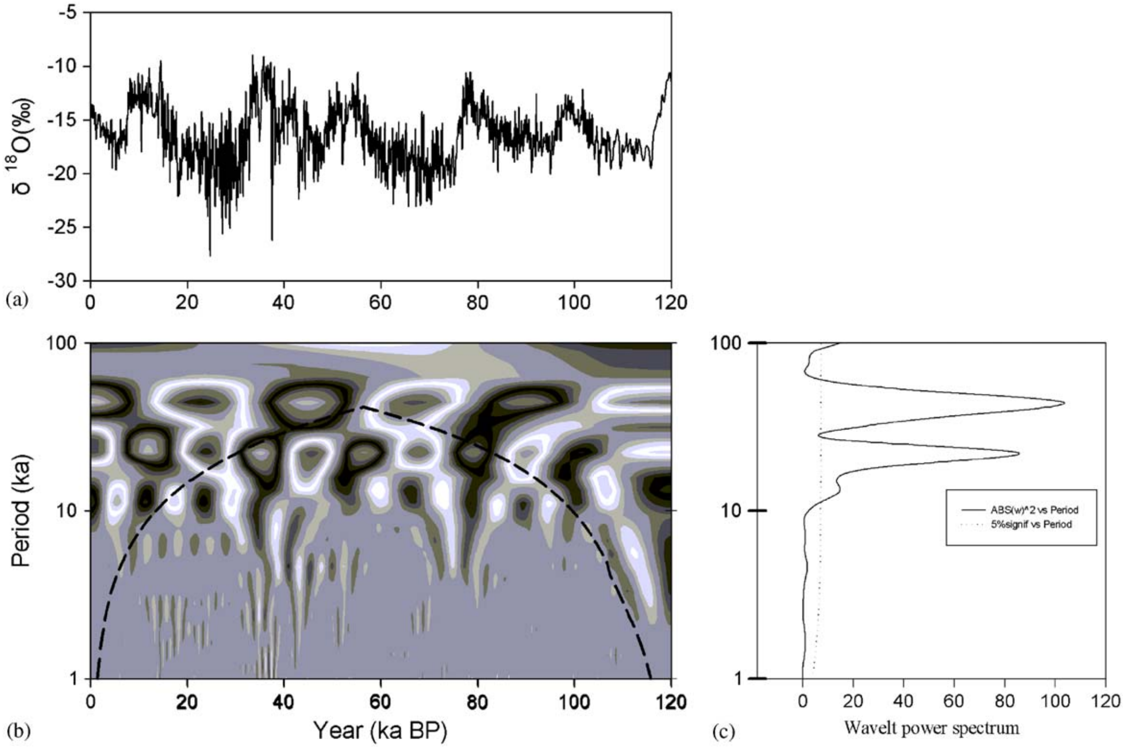

Fig. 2. $\delta^{18}O$ records in the past 120 kyr recorded in the Guliya ice core and wavelet results: (a) the $\delta^{18}O$ records (100 yr average); (b) the real part of the wavelet transform. The dark different shapes/contours of the gray area refer to the energy density of the corresponding period. The color reflects relative changes of the energy density; and (c) wavelet power spectrum, dashed line is 99% significant level.

which were marked by cold water foraminifera and ice-rafted lithic debris. Another marine core, drilled several hundred kilometers from the site of Heinrich's study, appeared to be stratigraphically similar (Broecker et al., 1992). Broecker (1994) indicated that the fresh water from the ice discharge and melting possibly disturbed the formation of deep water in the North Atlantic, thus affecting climate over large regions of the northern hemisphere. The intervals between H event reoccurrence averaged about 10 kyr (Hagelberg et al., 1994), but the interval between events 2 and 3 is an exception.

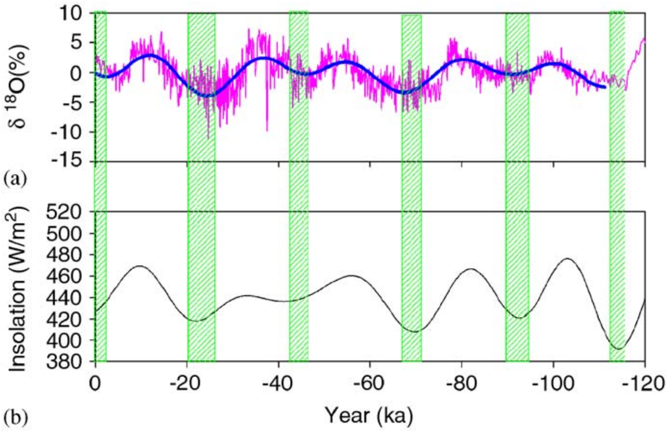

Fig. 3. Relationship between the precession and inclination components of the past 120 kyr as recorded in (a) the Guliya ice core and in (b) the solar insolation at 65°N (Berger, 1992). The raw $\delta^{18}O$ record in (a) is overlain by the combination of the two Milankovitch cycles in the data that were calculated by SSA.

Records from the Tibetan Plateau, such as that from the Guliya ice core, can be studied to determine whether climatic effects from Heinrich events extended outside the North Atlantic region. The time series from Guliya is considered to be of high resolution, and reflects the climatic changes on different time scales from the Last Interglacial (Eemian) to the Little Ice Age (Yao et al., 1997, 1997; Yao, 1999). Yao et al. (2001) demonstrated that Heinrich events were also clearly recorded by the stable isotope record from this ice core.

Fig. 5 shows the 13 kyr period component reconstructed by SSA. It explains ~6% of the total variance. Its amplitude varies with time, such that from 30 to 60 kyr the amplitude is small, but increases after 40 kyr. Here, using the wavelet analysis result, the climate oscillation features on sub-orbital time scales are discussed. In order to display the 13 kyr period component clearly, the real part of the wavelet transform which contains the periods between 0 and 20 kyr is shown in Fig. 6, where it is also

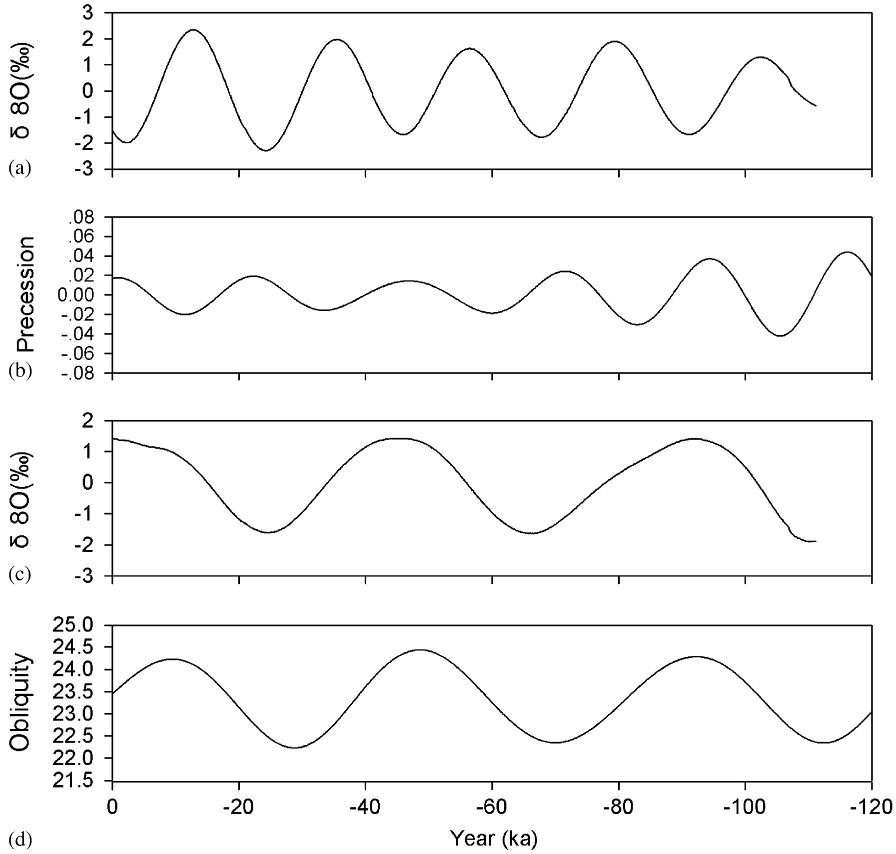

Fig. 4. Variations in the orbital precession and inclination (Berger, 1992), as well as their corresponding component over the past 120 kyr recorded in the Guliya ice core: (a) 22 ky precession period component in the Guliya ice core, compared with (b) the variation in the precession in the past 120 kyr; (c) 44 kyr inclination period component in the Guliya ice core, compared with (d) the variation in the inclination over the past 120 kyr.

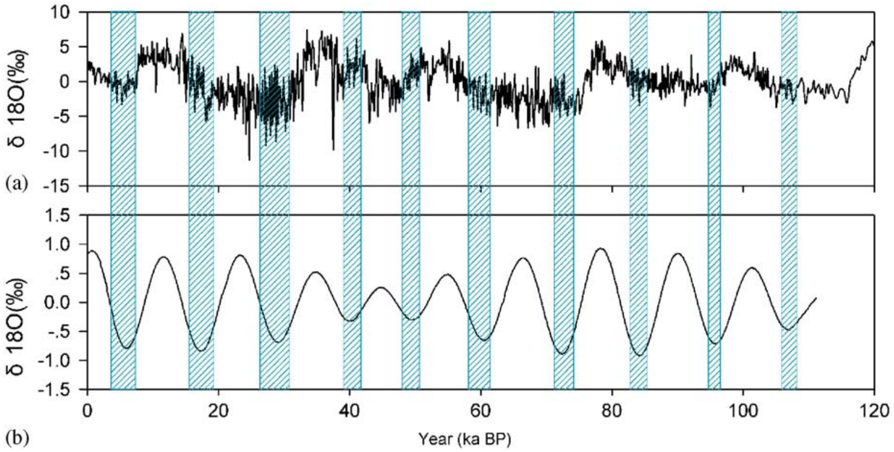

Fig. 5. A 13 kyr period component reconstructed by SSA from the Guliya ice core: (a) $\delta^{18}O$ records as shown in Fig. 2; (b) 13 kyr period component.

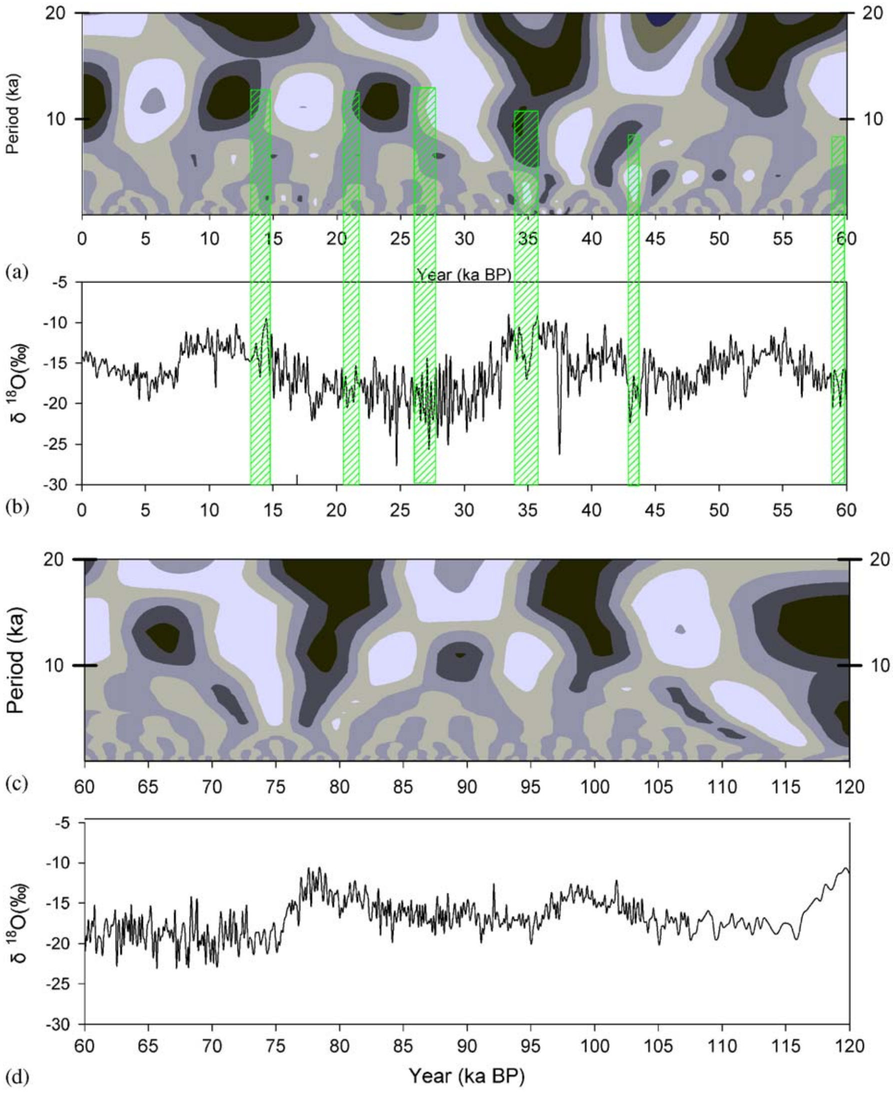

Fig. 6. The ~13 kyr period compared with the timing of Heinrich events in the Guliya ice core record. (a) Real part of the wavelet transform from 0 to 60 kyr. (b) $\delta^{18}O$ records from the Guliya ice core from 0 to 60 kyr. The cross-hatching indicates the Heinrich events. (c) Real part of the wavelet transform from 60 to 120 kyr. (d) $\delta^{18}O$ records in Guliya ice core from 60 to120 kyr.

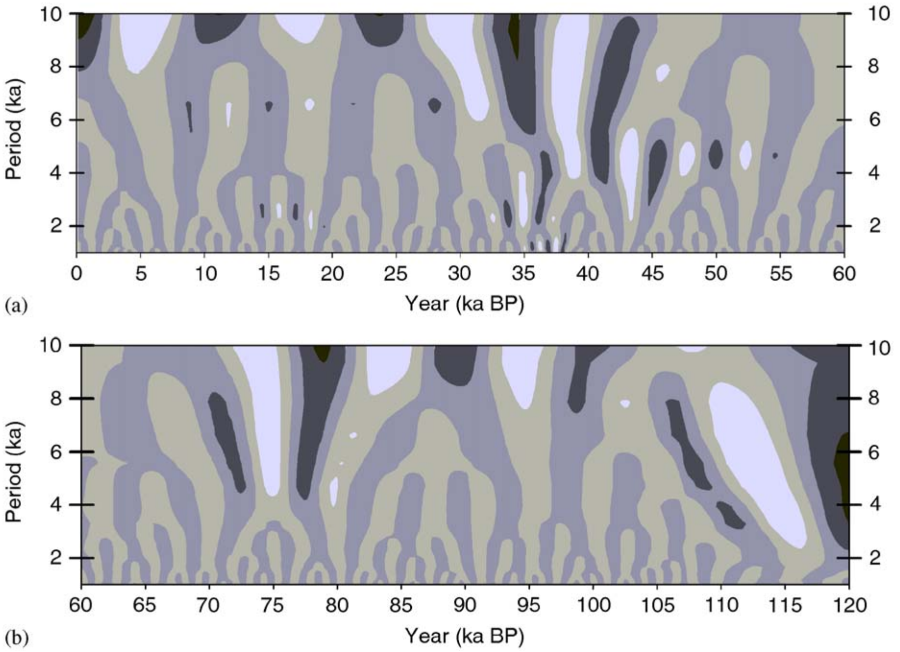

Fig. 7. Millennial time scale climate changes over the past 120 kyr recorded in the Guliya ice core: (a) real part of wavelet transform from 0 to 60 kyr; (b) real part of wavelet transform from 60 to 120 kyr.

compared with the timing of the H events (cross-hatched boxes). There are six events recorded during the Last Glacial cycle, at ~13–15, 21–22, 26–28, 34–36, 43–44 and 59–61 kyr (Boyle, 2000), and they correspond with significant cooling episodes depicted in the δ^{18}O profile. Furthermore, they also correspond to negative phases of the real part of wavelet transform. However, there are several similar isotopic depletions that do not appear to be timed to the Heinrich events (i.e. ~17–18, ~37–38 and ~52 kyr, although the ~37–38 kyr event is rather unique as discussed in Thompson et al., 1997). Conversely the 21–22 kyr H and especially the 26–28 kyr H are not very prominent in the ice core record. Therefore, it is worthwhile to examine in the future whether the isotopic lows between 10 and 60 kyr are also related to other factors. The variations in the amplitude of the 13 kyr periodicity approximately agree with those derived from the SSA method; it is small between 40 and 60 kyr, but after 30 kyr it gradually becomes more significant.

Paleoclimate records such as those derived from ice cores (e.g. Taylor et al., 1993) and deep sea sediments (e.g. Bond et al., 1993; McManus et al., 1994) demonstrate a series of abrupt climate changes on time scales of several centuries to millennia from the Last Glacial stage to the Eemian. Obviously, such millennial-scale events cannot be explained simply by variations in orbital parameters. Therefore, the study of abrupt climate shifts since 130 kyr has become one of the important, and most rapidly growing, aspects of paleoclimate research. According to the Greenland ice core δ^{18}O records, there were 24 abrupt warming events during the period between 115 and 14 kyr. Their average amplitudes range from 5 to 8 °C. Each warming period was followed by a cooling episode. These warm/cool cycles started within several decades or less and lasted up to 2000 yr, with an average period around 1500 yr (Dansgaard et al., 1993; Bond et al., 1997; Mayewski et al., 1997). Such corresponding changes in the sea surface temperature, iceberg discharge processes and the thermohaline circulation were also recorded by the deep sea sediments in the North Atlantic (Bond et al., 1993; Broecker, 1994; Bond and Lotti, 1995; Oppo and Lehman, 1995; Rasmussen et al., 1997).

Oscillations in the Guliya δ^{18}O record with periods less than 10 kyr (Fig. 2) are again displayed in Fig. 7. This much higher-resolution signal appears to be pervasive in the ice core, but the causes are subjects for future examination.

4. Discussion and conclusion

The acquiring of high-resolution, long-term climate series is very important for understanding climate changes. Although several long ice cores were recovered in Antarctica and Greenland and a series of results were published, the climate events recorded in their time series are asynchronous, i.e. their phases are different. How are the events recorded in Antarctic ice cores related to that in Greenland ice cores? In this case, the high-resolution and long-term climate series in mid and lower latitudes are needed. The Guliya ice core, which was recovered from the western Kunlun Shan on the Tibetan Plateau, allows reconstruction of climatic changes back to 120 kyr. Using the wavelet analysis and singular spectrum analysis methods, the oscillations recorded in the stable isotopes of this ice core were analyzed. The results appear to show that the Milankovitch orbital theory is the primary driver of the climate changes; i.e., the components of precession and inclination explain about 43% of the total variance. Furthermore, the variations of the compounding curve of the precession and inclination components are consistent with that of the insolation curve at 65°N. The Heinrich (H) events are also clearly recorded in the Guliya ice core. The 10 kyr H events intensified gradually from 120 to 60 kyr. From 60 to 40 kyr, they were considerably weaker, but intensified again after 40 kyr. Meanwhile, the wavelet analysis also shows that a millennial-scale periodicity is also evident in the Guliya ice core, although its mechanism requires further investigation.

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