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## High-frequency climatic fluctuations over the past 30 ka in northwestern margin of the East Asian monsoon region, China (Postprint)

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### Abstract

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## Full Text

# High-Frequency Climatic Fluctuations over the Past 30 ka in Northwestern Margin of the East Asian Monsoon Region, China

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## Abstract

Whether millennial- to centennial-scale climate variations throughout the Holocene convey universal climate change remains widely debated. In this study, we obtained high-resolution multi-proxy data (1,343 particle size samples, 893 total organic carbon samples, and 711 pollen samples) from an alluvial-lacustrine-aeolian sequence based on an improved age-depth model in the northwestern margin of the East Asian monsoon region to explore the dynamics of climate changes over the past 30 ka. Results revealed that the sequence not only documented major climate events that corresponded well with those reported from North Atlantic regions but also revealed many marked high-frequency oscillations at millennial and centennial scales. Specifically, the late stage of the last glacial lasting from 30.1 to 18.1 cal. ka BP was a dry and cold period. The deglacial (18.1–11.5 cal. ka BP) was a wetting (probably also warming) period, and three cold and dry excursions were found in this wetting trend: the Oldest Dryas (18.1–15.8 cal. ka BP), the Older Dryas (14.6–13.7 cal. ka BP), and the Younger Dryas (12.5–11.5 cal. ka BP). The Holocene can be divided into three portions: the warmest and wettest early portion from 11.5 to 6.7 cal. ka BP, the dramatically cold and dry middle portion from 6.7 to 3.0 cal. ka BP, and the coldest and driest late portion since 3.0 cal. ka BP. Wavelet analysis of total pollen concentration revealed five substantial periodicities: c. 5500, 2200, 900, 380, and 210 years. With the exception of the c. 5500-year quasi-cycle that was causally associated with Atlantic meridional overturning circulation, the other four quasi-cycles (c. 2200, 900, 380, and 210 years) were found to be indirectly associated with solar activities. This study provides considerable insight into the dynamic mechanisms of Asian climate on long timescales and future climatic change.

**Keywords:** East Asian monsoon region; total pollen concentrations; climate periodicity; millennial-centennial time scale; Chinese Loess Plateau

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## Introduction

The study of past climate change has improved our understanding of the mechanisms of the Earth's climate system (Ren et al., 2021). Climate change is unstable and quasi-periodic over longer timescales. Exploring the periods and mechanisms of climate change over longer timescales can not only contribute to understanding patterns and causes of past climate change but, more importantly, provide a scientific reference for predicting future climate and environmental changes. In recent years, different millennial-, centennial-, and decadal-scale quasi-periods have been found in high-resolution paleoclimate proxies from ice cores, stalagmites, tree rings, loess-paleosol, and lacustrine sediments. These quasi-periodic signals in climate change over different timescales may be linked to periodic signals of solar activity (Kravchinsky et al., 2013; Soon et al., 2014; Zhao and Feng, 2014; Zhang et al., 2017; Huang and Tian, 2018).

However, these studies primarily focused on the Holocene or middle and late Holocene. Accordingly, few studies have examined the periodicity of longer time sequences of high-resolution climate proxies prior to the Holocene. Therefore, whether millennial- to centennial-scale climate variations of the last 10,000 years convey universal climate change or merely represent a characteristic of the Holocene remains unknown (Kravchinsky et al., 2021).

The Earth's climate systems have experienced multiple major changes over the past 30 ka, primarily including the Last Glacial Maximum (LGM), the Last Deglaciation, and the Holocene Climatic Optimum. Superimposed on these major changes were abrupt oscillations at millennial and centennial scales (e.g., Heinrich Events, Dansgaard-Oeschger (D-O) Oscillations, and Holocene Bond Events). To explore the mechanisms related to these major changes and abrupt oscillations, we need high-quality data (i.e., high-resolution sampling, well-dated chronology, and adequately defined proxy) from locations that represent different geographic settings. Many high-quality paleoclimate sequences covering the past 30 ka have already been retrieved from various geographic settings, revealing certain basic characteristics of large-scale climate change over this period (Grootes et al., 1993; Bond et al., 1997, 1999; Liu et al., 2001; Wang et al., 2001; Dykoski et al., 2005; An et al., 2012). However, the locations of these sequences are not evenly distributed geographically. In particular, studies are lacking in mid-latitude regions that link high-latitude climate systems with low-latitude climate systems. To further improve our understanding of these major changes and abrupt oscillations, researchers must retrieve more high-quality paleoclimate sequences (especially high-resolution paleovegetation records) from mid-latitude regions, particularly from the margin of the East Asian monsoon region that is extremely sensitive to large-scale climate changes (Yang et al., 2019). Accordingly, the western part of the Chinese Loess Plateau, situated at the margin of the East Asian monsoon region, deserves more attention.

In this study, we aimed to re-examine previously reported major climatic and environmental changes (Wu et al., 2009; Sun and Feng, 2015; Wu et al., 2020) with an improved chronology and explore the periodicities of abrupt climatic and environmental oscillations expressed by data (e.g., particle size, total organic matter content, and pollen record) retrieved from an alluvial-lacustrine-aeolian sequence in the western part of the Chinese Loess Plateau.

## 2.1 Physiographic Settings

This study focuses on the Xiaogou (XG) section ( $36^{\circ}01'12''N$ ,  $104^{\circ}59'24''E$ ; 1625 m a.s.l.; Fig. 1 [Figure 1: see original paper]), an alluvial-lacustrine-aeolian sequence in the western part of the Chinese Loess Plateau. This area is located in the conjunctive zone of three major geographical regions of China: the humid monsoon region in the east, the arid region in the northwest, and the alpine-cold region on the Qinghai-Tibet Plateau. The western part of the Chinese Loess Plateau is topographically characterized by ridges and valleys, with elevations ranging from 1200 to 2500 m a.s.l., and climatically characterized by continental and semi-arid/semi-humid conditions. The annual mean temperature ranges from  $6^{\circ}C$  to  $10^{\circ}C$  in the Huajialing Mountains. However, mean annual precipitation markedly differs between the southeast (500–550 mm) and northwest (200–500 mm) in the Huajialing Mountains. Accordingly, the zonal vegetation in the southeast is temperate semi-humid forest or sparse forest steppe, whereas that in the northwest is temperate semi-arid and arid steppe (Wu et al., 1980). The dominant tree species in this region are *Quercus liaotungensis* Koidz., *Populus davidiana* Dode, *Betula platyphylla* Suk., *Platycladus orientalis* (Linn.) Franco, *Pinus tabulaeformis* Carr., and *Picea asperata* Mast., which primarily remain in the valleys (Chen et al., 2000).

## 2.2 Sedimentary Facies and Improved Age-Depth Model

The studied section (XG section) is a 40-m thick outcropping sediment along the Zuli River, a major tributary of the Yellow River. Based on lithofacies characteristics (e.g., color, lithology, and sedimentary structure), we divided the section into five stratigraphic units from bottom to top (Fig. 2 [Figure 2: see original paper]): (1) floodplain facies (40.0–32.4 m: brown-yellowish silt and clayey silt layer underlain by a gravel layer at the bottom), (2) shallow lake facies (32.4–21.8 m: light-black silty-clay and brown-yellowish silt alternating stratification), (3) deep lake facies (21.8–7.3 m: dark-black, light-black clay/silty-clay and brown-yellowish silt alternating stratification), (4) shallow lake facies (7.3–2.6 m: light-black, grey-greenish silty-clay, and brown-yellowish silt alternating stratification), and (5) aeolian loess (2.6–0.0 m: a massive yellowish clayey silt layer) (Wu et al., 2020). In the field, the lake-facies portion (32.4–2.6 m, units 2–4) formed at the outlet of the basin under a completely closed terminal lake when the Zuli River was dammed by a massive landslide (Wu et al., 2009, 2020).

A total of 23  $^{14}C$  dates (Table 1), including 19 previously reported dates (Wu

et al., 2009) and four newly obtained dates (i.e., AA87138, AA87139, AA87140, and AA87141 with \* in Table 1), are now available. All radiocarbon dates were calibrated to calendar years using IntCal20 (Reimer, 2020). After adding new dating data, we improved the original age-depth relationship model (Wu et al., 2009). The new age (A)-depth (D) model was established by adopting a unified nonlinear polynomial model for the calibrated dates, expressed as  $A = 1.2191 \times 10^{-3} D^3 - 6.2875 \times 10^{-2} D^2 + 1.3165 D + 0.9016$  (Fig. 2). Based on this model, we extrapolated the age of the section bottom at a depth of 40 m to be approximately 30 cal. ka BP (calendar age before present). Despite several inversions among the  $^{14}\text{C}$  ages, the newly established chronology of the XG section is reliable when considering the continuous deposition inferred from the horizontal layer structure of the XG section (Fig. 2).

### 2.3 Materials and Methods

The re-examined data employed in this study included 1,346 grain-size data (with an average interval of 3 cm and average resolution of 22 years/sample), 893 total organic carbon (TOC) data (with an average interval of 5 cm and average theoretical resolution of 34 years/sample), and 711 pollen data (with an average interval of 6 cm and mean resolution of 42 years/sample), which have been described in previous studies (Wu et al., 2009, 2020).

Generally, a coarser particle-sized lacustrine sedimentary unit formed during drier periods when the core site was closer to the lake water inlet because of lake shrinkage and/or when the drainage basin supplying water to the lake was poorly vegetated (Chen et al., 2004; Shen et al., 2010). For loess, the medium size (Md) is an indicator of winter monsoon intensity, and a coarser particle-sized loess unit is widely interpreted to indicate a drier and/or colder period when the winter monsoon is more intense (Ding et al., 1996; Chen et al., 1999). Loess and lacustrine alternating sedimentary units were interpreted to reflect periodical alternations between drier conditions (loess) and wetter conditions (lacustrine deposits) (Xia, 1992).

TOC content of lacustrine deposits normally reflects the input and retention of endogenous and exogenous organic matter, representing biological productivity within the lake and/or within the drainage basin supplying water to the lake. Higher TOC may indicate a better-vegetated drainage basin and/or a more productive lake environment (Shen et al., 2010). Consequently, TOC in lacustrine sequences within monsoon climate zones was interpreted to indicate vegetation coverage and biomass, thereby reflecting the amount of monsoon precipitation (Zhou et al., 1996, 1999; Guo et al., 2002).

Warmer and wetter environments were characterized by a general increase in watershed vegetation coverage, which led to an increase in total pollen concentration (TPC). Thus, an increase in pollen concentration corresponds to a relatively warmer and wetter climate (Tarasov et al., 2009; Bezrukova et al.,

2011; Kravchinsky et al., 2021). Variations in pollen concentration may reflect changes in vegetation coverage if both plant composition and deposition rate are somewhat constant. Higher vegetation coverage in monsoonal areas was interpreted to indicate higher effective humidity in the river basin (Li et al., 2000, 2003; Zhu, 2002; Shen et al., 2005; Chen et al., 2006; Luo et al., 2006).

Figure 3 [Figure 3: see original paper] shows that pollen concentrations (including total, coniferous, deciduous, shrubs and herbs, and some representative genera) align relatively well with TOC and Md. Higher TPC values align with higher TOC values and lower Md values. Notably, all lacustrine sub-units within the lacustrine-dominated sedimentary facies units (i.e., units 2, 3, 4 in Fig. 2) are basically characterized by lower Md values and higher values not only in TOC but also in TPC. Conversely, all loess sub-units within the lacustrine-dominated sedimentary facies units (i.e., units 2, 3, and 4 in Fig. 2) are basically characterized by higher Md values and lower values not only in TOC but also in TPC (see the shaded strips in Fig. 3).

In summary, higher TPC and TOC, and lower Md indicate stronger summer monsoons, higher vegetation coverage, and warm-wetter climate. In contrast, lower TPC and TOC, and higher Md indicate stronger winter monsoons, lower vegetation coverage, and relatively dry-colder climate.

### 3 Results and Discussion

The history of regional vegetation and climate changes recorded by pollen and other climatic data in the XG section was previously discussed (Wu et al., 2009, 2020). Based on the improved age-depth model established in this study, the vegetation and climate history over the past 30 ka in the study region are briefly summarized in Table 2 (pollen zone, see Fig. 3). In general, vegetation in the study area is very sensitive to climate change, and the forest/sparse forest steppe zone has advanced and retreated many times from southeast to northwest since the LGM (Wu et al., 2020). When the summer monsoon is enhanced, the climate becomes wet and warm, leading to the advance of the forest/sparse forest steppe zone from southeast to northwest; when the winter monsoon is enhanced, the climate becomes cold and dry, leading to the retreat of the forest/sparse forest steppe zone from northwest to southeast.

Based on this finding, we focused on abrupt climatic change events recorded by TPC, TOC, and Md of the XG section over the past 30 ka, their occurrence cycles, and their possible mechanisms (Figs. 4 and 5).

#### 3.1 Late Glacial and Heinrich Events

The floodplain facies (i.e., stratigraphic unit 1 in Figs. 2 and 3) formed during the late stage of the last glacial, lasting from 30.1 to 18.1 cal. ka BP. The corresponding particle size reached the coarsest part of the entire section, with low TPC and TOC (Fig. 3). These results indicate that the drainage basin of the Zuli River was rather poorly vegetated, and associated loess hill-slope

erosion effectively contributed to the floodplain deposits under extremely dry conditions, aligning with results from other parts of the Chinese Loess Plateau (Ding et al., 1996). However, this period (i.e., from 30.1 to 18.1 cal. ka BP) was not monotonously dry. Instead, two relatively humid intervals, characterized by relatively high values of coniferous pollen concentration and TOC, segmented this dry period into four epochs: a dry epoch in 30.1–29.0 cal. ka BP, a relatively wet epoch in 29.0–24.2 cal. ka BP, a dry epoch in 24.2–20.7 cal. ka BP, and a relatively wet epoch at 20.7–18.1 cal. ka BP (Fig. 3).

The proxy record curves from the XG section (i.e., Md, TOC, deciduous pollen percentage, and TPC) were compared with the  $\delta^{18}\text{O}$  curves of the Hulu Cave stalagmite (Wang et al., 2001), the  $\delta^{18}\text{O}$  curve from the Greenland ice core (Grootes et al., 1993), and the haematite-stained grain content curve from the North Atlantic deep-sea core (Bond et al., 1997) (Fig. 4). Figure 4 shows three Heinrich or Heinrich-like events at 29.5, 23.8, and 19.7 cal. ka BP (where corresponding Md reaches the coarsest points with low TPC and TOC). The first peak at 29.5 cal. ka BP appears to correspond with Heinrich Event 3 (H3), recorded not only in the North Atlantic region (i.e., deep-sea core and ice core) but also in the Chinese stalagmite region (i.e., Hulu Cave), whereas the second peak at 23.8 cal. ka BP corresponds approximately to H2. The third peak at 19.7 cal. ka BP, which is short but unequivocally expressed in the XG section, has no corresponding records from deep-sea and ice cores in the North Atlantic region.

### 3.2 Deglacial Wetting and Dryas Dry Events

The shallow lake facies (i.e., stratigraphic unit 2 in Figs. 2 and 3) formed during the last deglacial from 18.1 to 11.5 cal. ka BP. The declining trend of Md and increasing trends of TOC and TPC indicate that the climate was wetting (the appearance of deciduous broad-leaved tree pollen by *Quercus* indicates potential warming, see Figs. 3 and 4) during the deglacial. The proxy records also documented several dry excursions (indicated by low TOC and TPC values but high Md values) superimposed on the wetting trend. The first dry excursion lasted from 18.1 to 15.8 cal. ka BP, corresponding well with Heinrich Event 1 (H1 or the Oldest Dryas) (16.7 cal. ka BP) recorded not only in the North Atlantic region (i.e., deep-sea core and ice core) (Bond et al., 1997) but also in Chinese stalagmites (i.e., Hulu Cave) (Wang et al., 2001).

The proxy-documented dry interval was 14.6–13.7 cal. ka BP in the XG section, corresponding to the Older Dryas cold event (14.2–13.7 cal. ka BP) retrieved from the Greenland ice core (Grootes et al., 1993). The proxy-documented dry interval of 12.5–11.5 cal. ka BP corresponds to the Younger Dryas event (12.7–11.5 cal. ka BP) retrieved from the Greenland ice core (Grootes et al., 1993) and Chinese stalagmites (i.e., Hulu Cave and Dongge Cave) (Wang et al., 2001; Dykoski et al., 2005). Two intervening warm intervals retrieved from the North Atlantic region (Bond et al., 1997), namely the Bølling warm period and Allerød warm period (Stuiver et al., 1995; Li et al., 2004; Shen et al., 2005), were also

documented in the proxy records (indicated by higher TOC and TPC values but lower Md values) in the XG section (Fig. 4).

### 3.3 Holocene Climatic Optimum and Dry Events

The deep lake facies (i.e., stratigraphic unit 3 in Figs. 2 and 3) formed during the period from 11.5 to 6.7 cal. ka BP. The highest average values of TOC and TPC and a relatively high average value of deciduous pollen percentage (Figs. 3 and 4) imply that this time might represent the Holocene Climatic Optimum, with the warmest and wettest periods belonging to 9.5–6.7 cal. ka BP (maximum TPC occurred at approximately 9.0 cal. ka BP). The shallow lake facies (i.e., stratigraphic unit 4 in Figs. 2 and 3) formed during the period lasting from 6.7 to 3.0 cal. ka BP, overlying the deep lake facies. TOC and TPC values markedly decreased compared with those in the underlying deep lake facies (i.e., stratigraphic unit 3). This dry period (from 6.7 to 3.0 cal. ka BP) was most likely a cold period, as indicated by the nearly complete disappearance of deciduous pollen (Figs. 3 and 4). Aeolian loess deposition (i.e., stratigraphic unit 5 in Figs. 2 and 3) has dominated the XG section over the past 3,000 years. Low TOC and TPC values and an absolute lack of deciduous pollen suggest that the climate was dry and cold during the most recent 3,000 years.

Eleven dry episodes (i.e., D1–D11 in Fig. 4) were superimposed on the aforementioned general patterns of the Holocene (i.e., the warmest and wettest early portion, dramatically cooled and dried middle portion, and the coldest and driest late portion). These dry episodes were pronouncedly and unequivocally expressed by elevated Md values and lowered TOC and TPC values. Notably, although these 11 Holocene dry episodes in the XG proxy records do not correspond well with the eight Holocene Bond events in the North Atlantic haematite-stained grain content record (Bond et al., 1997), they correspond to approximately 11 cold-dry events reported from nearby Sujiawan and Dadiwan sections in the western part of the Chinese Loess Plateau (Tang et al., 2007). Furthermore, ice raft events recorded by floating ice debris in the North Atlantic are accompanied by relatively strong winter wind events in China; however, not all strong winter wind events have corresponding ice raft events (Chen et al., 2001). This finding also highlights the sensitivity and complexity of climate-environment changes in the arid and semi-arid areas of China. Notably, 6.7–5.5 cal. ka BP (i.e., D6 in Fig. 4), a period of prolonged climatic deterioration in the middle Holocene, is similar to the Younger Dryas event.

## 4 Climate Change Cycles

The advantage of wavelet analysis for detecting climatic periodicity has been demonstrated in numerous climatic records used to evaluate millennial and centennial cycles (Debret et al., 2009; Kravchinsky et al., 2021). TPC represents a superposition of various pollen taxa in the record and is sensitive to both temperature and moisture variations. TPC acts as a stacked climatic parameter that

smoothes the record while balancing out some uncertainties related to individual reactions of particular taxa to specific short-term conditions (Kravchinsky et al., 2021). As shown in Figure 4, although the TOC and TPC curves in the XG section are generally parallel to the summer insolation curve in the Northern Hemisphere (Berger, 1978), dramatic and frequent oscillations in the proxy records (i.e., Md, TOC, and TPC) can be readily observed throughout the entire XG section covering the past 30 ka. To explore the periodic characteristics of these dramatic and frequent oscillations, we used MATLAB to perform wavelet analysis (Torrence and Compo, 1998) on the TPC (2,991 equal time spacing (10-year) time series data after interpolation) of the XG section. Wavelet analysis revealed five significant or high-confidence millennial- and centennial-scale periodicities: c. 5500, 2200, 900, 380, and 210 years (Fig. 5a [Figure 5: see original paper]). At 95% confidence, we extracted the filtering curves of c. 5500, 2200, 900, 380, and 210 years (Fig. 5b).

First, the c. 5500-year quasi-cycle expressed in TPC data of the XG section is quite consistent with that of Heinrich Events, which are causally associated with Atlantic meridional overturning circulation (Grimm et al., 1993; Arbic et al., 2004), and roughly corresponds to the classical Bond cycle (Zeng et al., 2019). Second, the c. 2200-year quasi-cycle is quite similar to c. 2000-year cycles of ENSO (El Niño-Southern Oscillation) activity that might be associated with solar activity (Li et al., 2004; Wang, 2009), corresponds to the Dansgaard-Oeschger oscillation (Bond et al., 1999; Zeng et al., 2019), and is very close to the reported quasi-cycle of c. 2162 years of the East Asian summer monsoon (Zhang et al., 2017), which also aligns with the Hallstatt cycle (2215–2400 years) of total solar radiation variation (Zhang et al., 2017; Huang and Tian, 2018). Third, the c. 900-year quasi-cycle is consistent with the 1000-year cycle (Eddy cycle) of sunspot number and total solar radiation variation (Clemens, 2005; Zhang et al., 2017; Huang and Tian, 2018), which is not only confirmed by large Holocene climatic records but also reflected by high-pollen resolution records from Lake Kotokel in southern Siberia, Russia, during the LGM (Kravchinsky et al., 2021). Fourth, the c. 380-year quasi-cycle is very close to the c. 400-year quasi-cycle observed from the East Asian summer monsoon (Zhang et al., 2017), which may be equivalent to the unnamed period of approximately 350 years of solar total radiation amount (Huang and Tian, 2018). Fifth, the c. 210-year quasi-cycle might be a sensitive response to the Suess solar cycle (180–210 years, i.e., de Vries cycle) (Ojala et al., 2015), which is also reflected by high-pollen resolution records in the LGM (Kravchinsky et al., 2021).

Three points must be highlighted. First, the last three Heinrich events (H3, H2, and H1) occurred at the quasi-periodic trough of c. 5500 years, and the three Dryas events (Oldest Dryas, Older Dryas, and Younger Dryas) were basically consistent with a trough of the c. 2200-year quasi-cycle. Second, three shorter quasi-cycles (i.e., c. 900, 380, and 210 years) can explain most of the dramatic oscillations in the total pollen concentration data. Third, chronological additions of these five quasi-cycles mimicked the TPC curve well (Fig. 5c). In addition, the wavelet transformation and filtering curve revealed that two

millennial-scale quasi-periods (c. 5500 and 2200 years) were both stable and continuous for approximately 30 ka, indicating that these two periods are characteristic of regional climate change over the last 30 ka. The signal of a nearly millennial-scale quasi-cycle (c. 900 years) was weak in the LGM, gradually became stronger from the deglacial, and was continuously stable throughout the Holocene, which may be the main periodic signal for the Holocene. The signals of two shorter centennial-scale quasi-cycles (c. 380 and 210 years) were weak before the Holocene, strongest in the early and middle Holocene, and gradually weakened during the late Holocene (Fig. 5b). This variation also shows the complexity of regional climate change over long timescales.

In summary, the cold-dry climate events (H3, H2, H1, the Younger Dryas, and Holocene cold-dry events, etc.) revealed by high-resolution multi-proxy records (Md, TOC, and TPC, etc.) from the XG section are comparable to those noted in other records, such as deep-sea sediments in the North Atlantic, Greenland ice cores, and stalagmites from Hulu Cave and Dongge Cave, indicating teleconnection of climate change between mid-latitudes and high and low latitudes. The TPC curve from the XG section is parallel to the summer solar radiation curve in the mid-latitudes of the Northern Hemisphere, and the millennial- and centennial-scale quasi-cycles (i.e., c. 2200, 900, 380, and 210 years) from wavelet analysis on TPC also align with millennial- to centennial-scale quasi-cycles in solar activity, indicating that the source driving force of climate change may be solar radiation activity.

## 5 Conclusions

We analyzed high-resolution multi-proxy records (particle size, TOC, and pollen record) from an alluvial-lacustrine-aeolian sequence (i.e., XG section) based on an improved age-depth model in the western Chinese Loess Plateau, situated in the northwestern margin of the East Asian monsoon region. Our study revealed that the late stage of the last glacial from 30.1 to 18.1 cal. ka BP was generally a rather dry and cold period. Three Heinrich or Heinrich-like events (even drier and probably colder) occurred at 29.5, 23.8, and 19.7 cal. ka BP. The deglacial (from 18.1 to 11.5 cal. ka BP) was apparently a wetting (probably also warming) period, and superimposed on this wetting trend were three cold and dry excursions: the Oldest Dryas (or Heinrich Event 1), the Older Dryas, and the Younger Dryas. The intervening intervals were two warm periods: the Bølling and Allerød warm periods. The Holocene can be divided into three portions: the warmest and wettest early portion from 11.5 to 6.7 cal. ka BP, the dramatically dried and cooled middle portion from 6.7 to 3.0 cal. ka BP, and the driest and coldest late portion since 3.0 cal. ka BP. Eleven dry and cold episodes were superimposed on these general patterns. Wavelet analysis of TPC revealed five significant or high-confidence periodicities. Except for the c. 5500-year quasi-cycle similar to Heinrich events, the other four quasi-cycles (c. 2200, 900, 380, and 210 years) are most likely indirectly associated with solar activities. This study provides an important scientific reference for further in-

depth discussion of the mechanisms of regional climate change and prediction of future trends in climate and environmental change.

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