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The role of the Asian winter monsoon in the rapid propagation of abrupt climate changes during the last deglaciation

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A R T I C L E I N F O

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A B S T R A C T

High-resolution temperature records spanning the last deglaciation from low latitudes are scarce; however, they are important for understanding the rapid propagation of abrupt climate events throughout the Northern Hemisphere and the tropics. Here, we present a branched GDGTs-based temperature reconstruction from the sediments of Maar Lake Huguangyan in tropical China. The record reveals that the mean temperature during the Oldest Dryas was 17.8 °C, which was followed by a two-step increase of 2-3 °C to the Bølling-Allerød, a decrease to 19.8 °C during the Younger Dryas, and a rapid warming at the onset of the Holocene. The Oldest Dryas was about 2 °C warmer than the Younger Dryas. The reconstructed temperature was weighted towards the wintertime since the lake is monomictic and the mixing process in winter supplies nutrients from the lake bottom to the entire water column, greatly promoting biological productivity. In addition, the winter-biased temperature changes observed in the study are more distinctive than the summer-biased temperature records from extra-tropical regions of East Asia. This implies that the temperature decreases during abrupt climatic events were mainly a winter phenomenon. Within the limits of the dating uncertainties, the broadly similar pattern of winter-weighted temperature change observed in both tropical Lake Huguangyan and in Greenland ice cores indicates the occurrence of tightly-coupled interactions between high latitude ice sheets and land areas in the tropics. We suggest that the winter monsoon (especially cold surges) could play an important role in the rapid transmission of the temperature signal from the Arctic to the tropics.

1. Introduction

The last deglaciation is of great interest because the climate of the Northern Hemisphere experienced several distinct changes, such as the oldest Dryas (OD), Bølling, Older Dryas, Allerød, Intra-Allerød cold period and Younger Dryas (YD). Although great efforts have been made to understand these abrupt climate changes, the underlying dynamics, such as the trigger, amplification, propagation and termination, remain unclear. For example, three possible mechanisms (ocean thermohaline circulation, sea-ice feedbacks, and tropical processes) have been proposed for understanding rapid temperature shifts and their propagation throughout the Northern Hemisphere and the tropics (Chiang and Bitz, 2005; Broecker, 2006; Clement and Peterson, 2008). However, the sparsity of temperature time series from the Northern Hemisphere hampers our understanding of the underlying dynamics.

In the Arctic, traditional $\delta^{18}O$-based temperature reconstructions show that the YD was colder than the OD. This implies a muted climatic response to atmospheric CO_2, contrary to physical predictions of an enhanced high-latitude response to future increases in CO_2 (Liu et al., 2012; Buizert et al., 2014).

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Recently, a $\delta^{15}N$-based temperature reconstruction from Greenland ice cores indicated that the YD was about 4.5 °C warmer than the OD, contrary to the traditional $\delta^{18}O$ interpretation (Buizert et al., 2014). Additionally, it has been suggested that the reconstructed temperature in Greenland was dominated by severe winter conditions accompanied by relatively modest summer changes (Denton et al., 2005; Buizert et al., 2014).

Several studies of sea surface temperature (SST) variations in the South China Sea have been undertaken and it has been suggested that the variations were driven by different factors, including the winter monsoon (e.g. Steinke et al., 2008), summer monsoon (Oppo and Sun, 2005), ENSO variability (Rosenthal et al., 2003), or sea level changes (Zhao et al., 2006).

In the land area of Asia, only a few high-resolution quantitative temperature records extend to the last deglaciation, although stalagmite $\delta^{18}O$ records reveal distinct hydrological changes (e.g. Wang et al., 2001; Dutt et al., 2015). This sparsity of high-resolution quantitative temperature records hampers our understanding of how temperature shifts were rapidly transmitted to tropical Asia.

Maar lakes are recognized as ideal sites for the preservation of high-resolution sediment archives because they are closed basins with a relatively simple hydrological system and they provide continuous sedimentary sequences (Chu et al., 2002; Yancheva et al., 2007). Huguangyan Maar Lake in tropical South China has been the subject of numerous studies. Most of the paleoclimatic studies have focused on paleo-monsoon changes, although there is an ongoing debate regarding the interpretation of the proxies (magnetic susceptibility and Ti content) as indicators of the strength the East Asian Winter Monsoon (EAWM) (Yancheva et al., 2007) or the East Asian Summer Monsoon (EWSM) (Zhou et al., 2009; Wu et al., 2012; Shen et al., 2013; Duan et al., 2014; Jia et al., 2015). Based on records of magnetic susceptibility and Ti content from the sediments of Huguangyan Maar Lake, Yancheva et al. (2007) found evidence for stronger winter monsoon winds before the Bølling–Allerød warming, during the YD episode, and during the middle and late Holocene, as well as an inverse correlation between the summer and winter monsoons. A recent diatom record indicated that the EAWM was antiphased with the EASM during the last deglaciation, but that there was a complex relationship between the two during the early and middle Holocene (Wang et al., 2012). However, isotopic evidence ($^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$) indicated that the lithogenic source of the sediments is mainly from local pyroclastic material (e.g. Zhou et al., 2009; Wang et al., 2016a), and not from arid areas in northern China as proposed by Yancheva et al. (2007). Shen et al. (2013) noted that monsoon-induced changes in vegetation density predominated over runoff in controlling Ti input. Thus, the nature of paleo-monsoon changes in the region remains unclear.

Branched glycerol dialkyl glycerol tetraethers (brGDGTs) are membrane lipids of bacteria, and occur ubiquitously in the terrestrial environment, such as in lake sediments, soils and river sediments (Hopmans et al., 2004; Weijers et al., 2007; Tierney and Russell, 2009, 2010; Sinninghe Damsté et al., 2009; Yang et al., 2013; Schouten et al., 2013; Sanchi et al., 2014). Numerous studies have demonstrated that the brGDGTs-based index from lacustrine sediments can be used to reconstruct paleotemperatures (Tierney et al., 2010; Pearson et al., 2011; Sun et al., 2011; Loomis et al., 2012; Kaiser et al., 2015; Hu et al., 2016), and the proxies are increasingly being used for quantitative temperature reconstruction from lake sediment cores (Sinninghe Damsté et al., 2012; Woltering et al., 2014; Sanchi et al., 2014. Colcord et al., 2015; Hu et al., 2015). Here, we present a brGDGTs-based temperature reconstruction spanning the last deglaciation from Huguangyan Maar Lake, and use the record to help understand the rapid propagation of temperature changes from high latitudes to tropical Asia.

2. Study site

Huguangyan Maar Lake (21°9′N, 110°17′E) is located on the Leizhou Peninsula in the tropical region of South China (Fig. 1). The lake is a closed basin and has a surface area of 2.3 km^2 and a maximum depth of 22 m. In summer, the climate is influenced by both the subtropical summer monsoon (the East Asia summer monsoon) and the tropical summer monsoon (the South China Sea summer monsoon and the Indian summer monsoon) (Fig. 1). Atmospheric water vapor sources are mainly from the subtropical Pacific, South China Sea and Indian Ocean (Chen et al., 1991; Liu, 2010). In winter, cold air associated with the development of the Siberian High penetrates the region via two paths: one from northern China, and the other along the coast of East Asia (Fig. 1). The averaged mean annual air temperature (MAAT) is 23.4 °C, and the temperature difference between winter and summer is 11.9 °C (1964–2004, in Zhanjiang meteorological station), and about 48% of the mean annual precipitation of 1689 mm falls between June and August.

3. Methods

3.1. Sediment cores and chronology

Overlapping piston cores of sediment were collected from a water depth of 14.0 m near the center of the lake in September 2011. The results of radiometric dating (^{137}Cs, ^{210}Pb, AMS^{14}C) have been presented previously (Wang et al., 2016a), except for two radiocarbon ages from charcoal samples from sediment depths of 935 and 1029 cm. The chronology is based on linear interpolation of radiocarbon ages from leaves, other plant remains, and charcoals (Fig. 2).

3.2. GDGT extraction and analysis

The cores were split in half longitudinally and one half of the core was used for geochemical analyses at a 1-cm interval. All samples were freeze dried before extraction. Following Weijers et al. (2007), aliquots of freeze-dried samples were extracted during two cycles with an accelerated solvent extractor (ASE, DIONEX350) together with a mixture of dichloromethane DCM/MeOH 9:1 (v/v) at 100 °C and 7.6 × 10^6 Pa. The total extracts were rotary evaporated in near-vacuum and separated over an activated Al_2O_3 column, using DCM and DCM/methanol 1:1 (v/v), into an apolar and a polar fraction, respectively. The polar fraction was dried under a continuous N_2 flow, and was then ultrasonically dissolved in a hexane/propanol 99:1 (v/v) mixture with a C46 GDGTs added as internal standard and filtered through a 0.45 μm PTFE filter (ø 4 mm) prior to analysis.

Branched GDGTs were analyzed using high performance liquid chromatography/atmospheric pressure chemical ionization - mass spectrometry (HPLC/APCI-MS-MS) with an Agilent 1200 series/ABI4000 instrument equipped with an automatic injector and Analyst 1.5 software, according to Hopmans et al. (2004) and Weijers et al. (2007), with modifications. Separation was achieved using a Grace Prevail Cyano column (150 mm × 2.1 mm; 3 μm). The flow rate of the hexane/propanol 99:1 (v/v) eluent was 0.2 ml min^{-1}, thereafter with a linear gradient to 5% propanol in 40 min. Ion scanning was performed in a single ion monitoring mode. BIT, CBT, and MBT were calculated following Hopmans et al. (2004) and Weijers et al. (2007). Quantification was determined

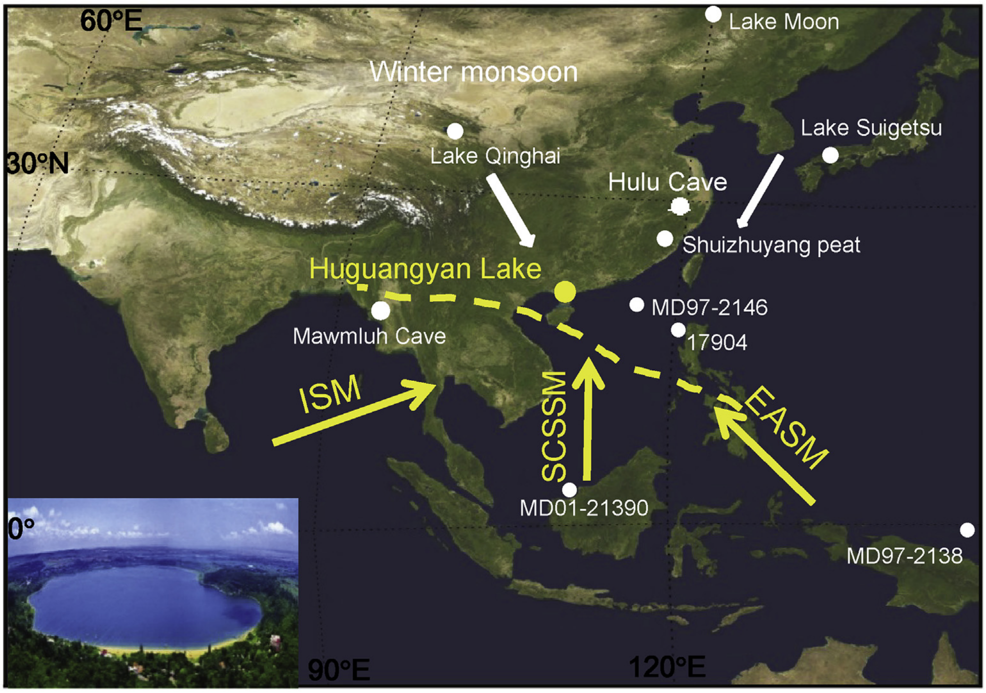

Fig. 1. Location of Maar Lake Huguangyan, and paleoclimatic records mentioned in the text. Solid arrows indicate the dominant direction of the summer monsoon (yellow) and winter monsoon (white). The dashed yellow line shows the modern mean position of the ITCZ in July (Liu, 210). The inset photo shows Lake Huguangyan. The background image is modified from NASA (http://visibleearth.nasa.gov). The white circles indicate the locations of paleoclimatic records discussed in the text. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

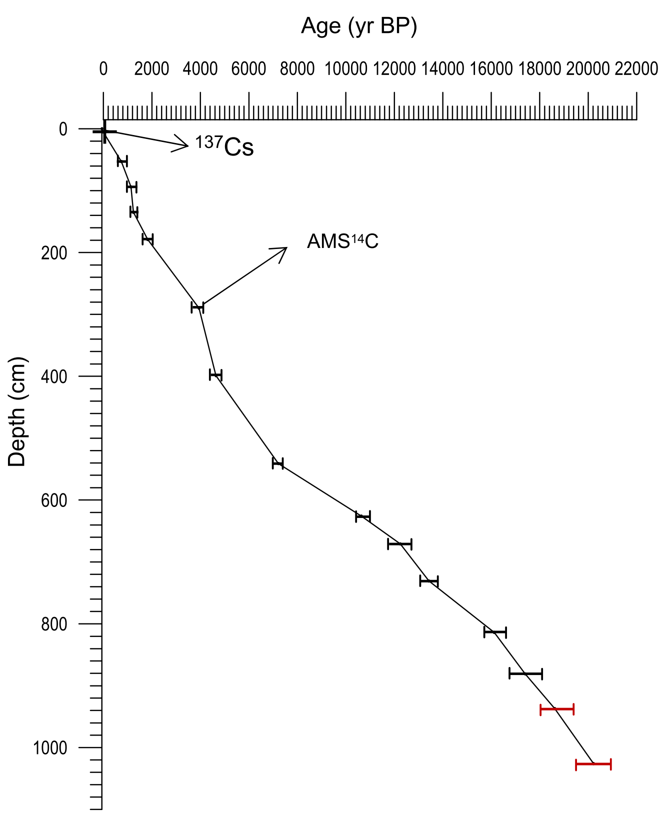

Fig. 2. Age-depth plot for Maar Lake Huguangyan. The AMS ^{14}C dates were calibrated using CALIB 4.3 (Stuiver et al., 1998) and are shown with 2 sigma error bars. The data have been presented previously (Wang et al., 2016a), except for two radiocarbon ages (brown) from charcoal samples from sediment depths of 935 and 1029 cm.

using the C46 standard.

4. Results and discussion

4.1. Distribution of GDGTs

The GDGT composition of the Huguangyan lake sediments is dominated by brGDGTs (up to 85% of total GDGTs) (Fig. 3). The concentrations of brGDGTs range from 0.64 to 29.4 μg/g, with a mean of 8.6 μg/g. Higher concentrations of brGDGTs occurred during the transition from the Oldest Dryas (OD) (18.2–15.5 kyr BP) to the Bølling-Allerød (BA) (14.6–12.8 kyr BP), and in the Early Holocene (11.4–10.0 kyr BP); while low concentrations occurred during the latest part of the last glacial (20.0–15.5 kyr BP) and the Younger Dryas (YD) (12.8–11.4 kyr BP) (Fig. 3).

The BIT index, the ratio of branched and isoprenoid tetraethers, has been suggested as a proxy for estimating the relative contributions of soil and aquatic sources to lake sediments (Hopmans et al., 2004; Sinninghe Damsté et al., 2012). In the sediment core from Lake Huguangyan, the BIT ranged from 0.96 to 1.00, with lower values during the lateglacial (20.0–15.5 kyr BP), and high values (above 0.99) after 15.5 kyr BP (Fig. 3). These values are close to those of suspended particulate matter with values ranging from 0.99 to 1.00, but are slightly higher than those from the soils in the Lake Huguangyan catchment (mean = 0.93) (Hu et al., 2016). Since the soils in the lake catchment are developed from tephra deposits which are enriched in primary ferrimagnetic minerals, the magnetic susceptibility of the lake sediments is a good indicator of soil input. The magnetic susceptibility and BIT values exhibit a relatively similar pattern of variation between 19.7 and 12.8 kyr BP, but this is less clear during the YD (Fig. 3). Considering the small difference between the BIT index of the soils (mean = 0.93) and the lake sediments (mean = 0.99) in the lake, the index may not be a reliable estimate of the relative contributions of soil and aquatic

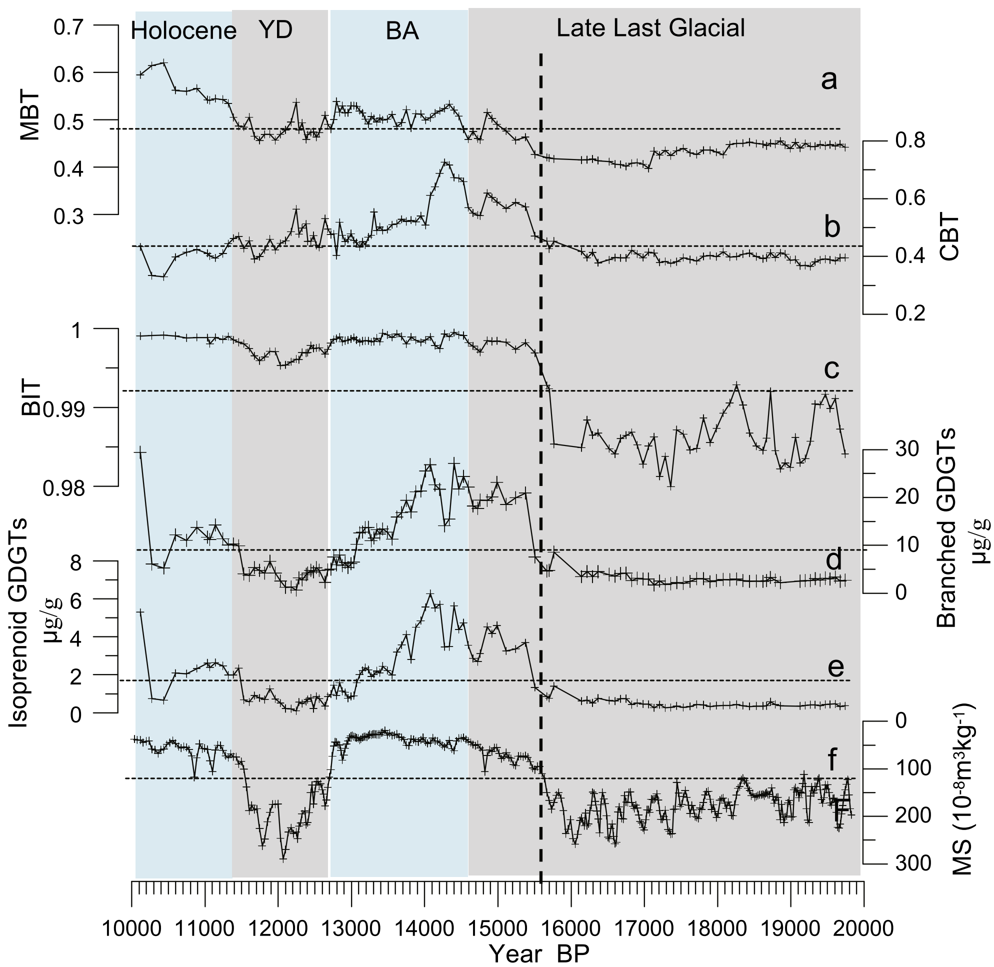

Fig. 3. Variation in GDGTs and sedimentary clastic content during the last deglaciation. (a) MBT; (b) CBT; (c) BIT; (d) isoprenoid GDGTs; (e) branched GDGTs; (f) magnetic susceptibility. Dashed lines are the mean values.

sources.

The CBT values of the sediments vary between 0.33 and 0.73, with relatively high values during the interval from 15.5 to 11.4 kyr BP in the lake (Fig. 3). It has been suggested that the CBT index relates mainly to lake pH (Tierney et al., 2010; Sun et al., 2011; Schoon et al., 2013). In saline and alkaline lakes (high pH conditions), however, a positive correlation between CBT and pH has been observed (Günther et al., 2014). A possible mechanism has been proposed to explain the opposite relationship between CBT and pH in lakes: brGDGTs-producing bacteria can use Na for energy transduction under high pH conditions to overcome H^+ leakage (Schoon et al., 2013).

Recently, De Jonge et al. (2014) found that the 6-methyl brGDGTs account for a large proportion of the total brGDGT inventory, particularly in alkaline soils. They suggested that separate quantification of the 6- and 5-methyl brGDGTs is essential for accurately quantifying brGDGTs in environmental samples and results in substantially improved MAT and soil pH reconstructions (De Jonge et al., 2014). A recent study suggested that the proportion of 6-methyl brGDGTs in alkaline soils was associated with high soil pH rather than with aridity in soils on Mt. Shennongjia (Wang et al., 2016b). However, the methylation degree of 5-methyl brGDGTs exhibits no relationship with MAAT, whereas the methylation degree of 6-methyl brGDGTs is significantly correlated with MAAT in Chinese lakes (Dang et al., 2016). This is the opposite situation to that observed in global soils (Dang et al., 2016). Considering that the presence of 6- and 5-methyl brGDGTs in lakes and their relationship with climatic or environmental variables remain unclear, caution is needed when using them in a calibration. More research is needed to evaluate climatic or environmental controls on the presence of 6- and 5-methyl brGDGTs in lakes.

Previous studies have indicated that the MBT index in lakes is primarily associated with mean annual temperature (Tierney and Russell, 2009; Blaga et al., 2010; Sun et al., 2011; Loomis et al., 2012). The MBT values of Huguangyan Lake range from 0.40 to 0.62 with a mean of 0.48. Lower MBT values occur in cold intervals such as the latest part of the last glacial and the YD, while high values occur in the BA and early Holocene (Fig. 3).

4.2. Temperature calibration

Many calibrations have been developed for estimating temperature from brGDGTs in soils and lakes (e.g., Weijers et al., 2007; Tierney et al., 2010; Günther et al., 2014). However, it is clearly better to use a calibration derived from lakes when the contribution of aquatic brGDGTs to lake sediments is higher than that from soils. In Lake Huguangyan, the concentrations of brGDGTs in the sediments range from 725.1 to 2008.6 ng g^{-1} dry weight, while the concentrations in the soils range from 33.2 to 259.2 ng g^{-1} dry weight (Hu et al., 2016).

Based on the distribution of brGDGTs in lake sediments, several calibrations have been developed for estimating palaeotemperatures (Tierney et al., 2010; Zink et al., 2010; Pearson et al., 2011; Sun et al., 2011; Loomis et al., 2012; Günther et al., 2014). However, there are many uncertainties in previous temperature calibrations when they are applied to a given lake. The calibrated temperatures from different lacustrine settings may be biased by factors such as seasonality of primary production and/or the preferred depth habitat of the related microorganisms (Sun et al., 2011). To choose an appropriate calibration, we compared the reconstructed temperature of core-top sediments with the mean annual air temperature using different calibrations. The results are listed in Table 1 and they reveal large differences between different calibrations. This is not surprising since there are large differences in climatic background, limnological conditions and source organisms among the different datasets. In Lake Huguangyan, one problem is the uncertainty in the instrumental temperature dataset because of the urban heat island effect. A large temperature difference between urban and rural temperatures (a mean of 6.5 K from AD 2000 to AD 2010) has been observed in Nanning city (22°13′N, 108°30′E) (about 270 km from Lake Huguangyan) (Lin et al., 2014).

There is a significant difference between the results of Sun et al. (2011) and Hu et al. (2015). The reconstructed temperatures for lake surface sediments (Hu et al., 2016) ranged from 22.5 to 25.0 °C, with a mean of 23.4 °C, using the equation of Sun et al. (2011); this is close to the observed MAAT at Zhanjiang meteorological station. However, the reconstructed temperatures could be lower if the temperatures were weighted by seasonal brGDGTs fluxes. In fact, Hu et al. (2016) stressed that the maximum concentrations and fluxes of branched GDGTs occurred during the winter months, when the water column was well mixed due to the strong EASM. In addition, the core-top samples of Sun et al. (2011) were collected in 2001, while the samples of Hu et al. (2015) were collected more recently. We attribute the difference between the two sets of results to increased soil inputs to the lake, because in the recent past the catchment has been significantly affected by human activity. This includes the construction of a road encircling the lake, gardens, a museum, and the collection of over 100 sediment cores. The soil samples have higher MBT values (mean = 0.90) than the lake sediments (~0.56) (Hu et al., 2016), and therefore an increase in soil-derived brGDGTs would result in higher temperatures being recorded in the surface sediments using the MBT/CBT based calibration.

As discussed above, in the present study we prefer to use a sediment-based calibration model (from lakes with pH < 8.5) (Sun et al., 2011) for reconstructing temperature during the last deglaciation, although a close to 'instrumental MAAT' has been obtained using a MBT-CBT based calibration from all lakes (Sun et al., 2011), or using a MBT-CBT based calibration from Chinese-Nepalese lakes (Sun et al., 2011) (Table 1).

4.3. Effect of seasonality on brGDGTs production

Many temperature proxies are controlled by seasonal processes and consequently they impart biases to the reconstructed temperature series. In the case of the branched GDGTs-based temperature indicator, previous work has considered the influence of seasonality on the production of brGDGTs in lakes and soils (Weijers et al., 2011; Sinninghe Damsté et al., 2012; Shanahan et al., 2013; Peterse et al., 2014; Sanchi et al., 2014). Recent observations have revealed a seasonal trend in brGDGTs production, with production in soils mainly occurring in the growing season or the warm season (spring, summer and autumn) in the Asian monsoon region (Wang et al., 2016b; Deng et al., 2016); this is because the soils are frozen during winter. In addition, the brGDGTs produced in lakes may be more sensitive to seasonal variations than brGDGTs produced in soils (Peterse et al., 2014).

It has been suggested that the brGDGTs-producing bacteria in limnic systems may be abundant and metabolically active during the warmer seasons in higher latitudes than most of the extra-tropical region (e.g. Rueda et al., 2009; Sun et al., 2011; Shanahan et al., 2013; Peterse et al., 2014). Such seasonal biases could be mainly due to seasonal changes in primary production that are primarily related to changes in limnological characteristics and nutrient levels. However, seasonal changes in production vary between different lakes and regions. In the extra-tropical region, brGDGTs are probably produced in the warmer seasons (Sun et al., 2011; Shanahan et al., 2013).

In tropical regions, temperatures are suited to organism growth throughout the year. However, it should be noted that in any particular lake, seasonal changes in primary production vary with different limnological conditions (e.g., in monomictic, dimictic, polymictic, holomictic and amictic lakes). Lake Huguangyan is a monomictic lake and is thermally stratified for most of year (Chu et al., 2002); the mixing process mainly occurs in winter. In the mixing period, nutrients are transported from the lake bottom and are mixed throughout the water column, which greatly facilitates biological productivity. This process has been confirmed in two independent sediment trap studies. For example, monthly observation evidence showed that planktonic diatoms are abundant during winter because of the effect of winter monsoon conditions causing nutrient-rich bottom water to reach the surface (Wang et al., 2012). A recent sediment trap study showed that the fluxes of brGDGTs in winter (mean = 18.3 μg.m-^{2}. day^{-1}) were more than twice as high as in summer (mean = 6.8 μg m^{-2}. day^{-1}) (calculated from Fig. 3B in Hu et al., 2016). This provides robust evidence for the reconstructed temperature being weighted towards the

Table 1
Branched GDGTs-based temperature estimates for core-top sediments from Maar Lake Huguangyan.

Samples	MBT	CBT	MAAT[a]	MAAT[b]	Tw[c]	MAAT[d]	MAAT[e]	MAAT[f]	MAAT[g]	T[h]	MAAT[i]
Sun et al., 2011	0.41	0.35	19.5	17.7	21.3	21.9	33.5	16.5	21.1	27.711.1	
Hu et al., 2015	0.56	0.34	25.2	23.4	28.5	26.9	34.5	24.8	25.0	33.5	18.7

Note: The mean annual air temperature (MMAT) is 23.4 °C (1964–2004, Zhanjiang weather station, about 15 km from Lake Huguangyan).
[a] MBT-CBT based calibration from all lakes (Sun et al., 2011).
[b] MBT-CBT based calibration from lakes with pH < 8.5 (Sun et al., 2011).
[c] MBT-CBT based calibration from Chinese-Nepal lakes (Sun et al., 2011). Mean air temperature in warm months (Tw) (warm month means that average monthly air temperature is more than 0 °C) (Sun et al., 2011).
[d] MBT-CBT based calibration (Tierney et al., 2010).
[e] Three major branched GDGTs (GDGTs I, II, and III) based calibration (Tierney et al., 2010).
[f] MBT based calibration (Zink et al., 2010).
[g] Three major branched GDGTs based calibration (Loomis et al., 2012).
[h] Three major branched GDGTs based calibration (Pearson et al., 2011).
[i] MBT-CBT based calibration from soils (Weijers et al., 2007).

wintertime. Although we know little about the behavior of the source organisms of branched GDGTs, we can assume that nutrient availability (mainly regulated by limnological processes) is one of most important factors for brGDGTs-producing organisms. Therefore, the MAAT in this study may be weighted towards the winter, especially under the conditions of a stronger winter monsoon during the last deglaciation.

4.4. Comparison of the brGDGTs-based temperature reconstruction with monsoon proxy records

The reconstructed MAAT indicates two cold intervals, corresponding to the OD (18.1–15.5 kyr BP) and the YD (12.8–11.4 kyr BP), and warm intervals in the BA (14.6–12.8 kyr BP) and the Early Holocene (Fig. 4). A two-step increase of 2–3 °C occurred at the onset of the BA (15.5–14.9 kyr BP and 14.4–14.6 kyr BP). The reconstructed temperatures during the OD and YD are about 5.6 °C and 3.5 °C colder than modern temperatures, respectively (Fig. 4). In addition to the well-documented YD, the OD (the coldest stadial after the Weichselian glaciation in Europe) is less stressed in monsoon records. Several stalagmite $\delta^{18}O$ records both from the EASM region (Wang et al., 2001) and the Indian summer monsoon (ISM) region (Dutt et al., 2015) are characterized by higher $\delta^{18}O$ during the OD. This was also observed in a magnetic susceptibility record from Lake Huguangyan (Wang et al., 2016a) (Fig. 4). The similar pattern of variations between the branched GDGTs-based temperature and stalagmite $\delta^{18}O$ values suggests that colder temperatures may have reduced the land-sea thermal contrast and weakened the EASM (Wang et al., 2001). However, there is an ongoing debate as to whether the variations in stable oxygen isotopes reflect monsoon strength. In addition, the present summer climate of the region is influenced by both the subtropical and tropical summer monsoon, which are physically derived by distinct forcing mechanisms (Chen et al., 1991) (Fig. 1). The brGDGTs-based temperature reconstruction may be insufficient to consider summer monsoon variations in different sub-monsoon systems.

Is well recognized that the EAWM is mainly controlled by ice volume or ice sheet dynamics (Ding et al., 1995). An increase in ice volume or the expansion of ice sheets would cool the air at high latitudes and strengthen the EAWM (Ding et al., 1995). In Huguangyan Maar Lake, previous arguments have focused on whether the sedimentary Ti content is an indicator of the winter monsoon (Yancheva et al., 2007), of monsoon-induced vegetation density (Shen et al., 2013), or of surface runoff (precipitation) (Zhou et al., 2009; Duan et al., 2014).

Huguangyan is a small hydrologically-closed lake with no

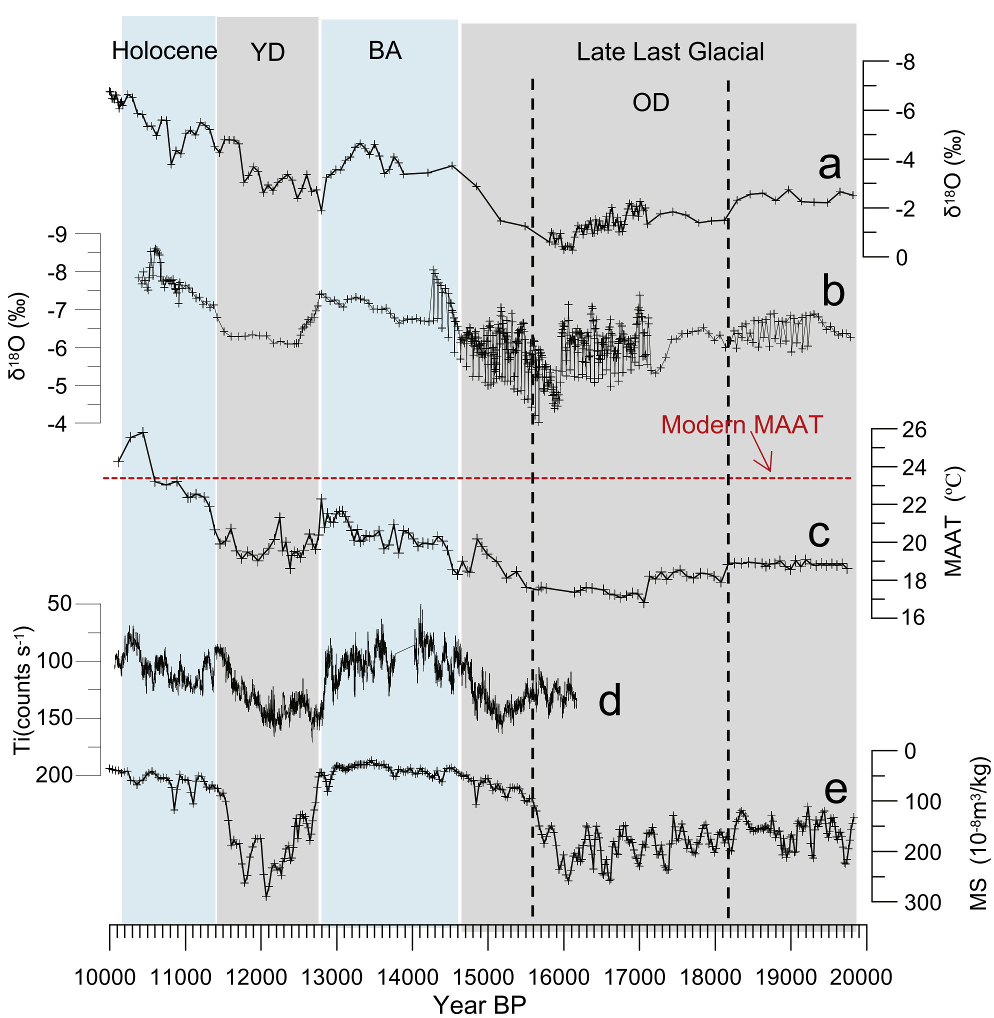

Fig. 4. Comparison of the reconstructed MAAT time series with monsoon proxy records. (a) Stalagmite $\delta^{18}O$ record from Mawmluh Cave, close to the Bay of Bengal (Dutt et al., 2015). (b) Stalagmite $\delta^{18}O$ record from Hulu Cave (Wang et al., 2001). The $\delta^{18}O$ data from 10,540 to 14,940 year BP are from sample H82; the $\delta^{18}O$ data from 14,940 to 20,006 year BP are from samples MSD, PD and YT (Wang et al., 2001). (c) MAAT estimated from brGDGTs (this study). (d) Ti concentration record for Lake Huguangyan (Yancheva et al., 2007). (e) Magnetic susceptibility record for Lake Huguangyan (Wang et al., 2016a,b).

outflow and inflow, and the supply of clastic sediment to the lake center mainly results from currents and waves activity caused by wind stress (supporting Fig. S1). This phenomenon is common in lakes since water has a higher density than air (by a factor of ~800). Surface currents tend to follow the dominant northeast wind direction (Wang et al., 2012), bottom currents move against the dominant wind direction (when the lake water is stratified, they move along the epilimnion) and transport fine clastic material from the nearshore zone to the lake center, leaving coarse clastic material (sand) as a residue (supporting Fig. S1). Therefore, an increased winter wind speed would lead to stronger lake currents and the increased transport of particles from the nearshore zone to the lake center.

Variations in monsoon-controlled vegetation density may be a secondary factor in controlling clastic inputs and Ti in this closed lake. Vegetation density in the catchment of maar lakes is often high because the moisture derived from strong evaporation from the lake surface promotes vegetation growth. For example, there is dense tropical forest in the catchment of tropical Maar Lake Twintaung (22°22′N, 95°02′E) in a dry area of Myanmar (supporting Fig. S2) (Sun et al., 2016). The annual precipitation at the site is only 757 mm, much less than at Maar Lake Huguangyan (1689 mm); however, plants grow well in the catchment.

In conclusion, the branched GDGTs-based temperature time series from Maar Lake Huguangyan supports a previous climatic interpretation: that strong winter monsoon winds occurred during colder intervals such as the YD and OD (Yancheva et al., 2007; Wang et al., 2012).

4.5. Comparison of the winter-biased temperature record from tropical Lake Huguangyan and summer-biased temperature records from extra-tropical areas

The assessment of spatial variations in temperature across different latitudes may be useful for evaluating the seasonal biases in proxy-based temperature reconstructions. Next, we compare the brGDGTs-based temperature record from tropical Lake Huguangyan with temperature anomalies estimated from a pollen record from Lake Moon (Wu et al., 2016), an alkenone-based summer temperature record from Lake Qinghai (Hou et al., 2016), a high-resolution pollen-based summer temperature record from Lake Suigetsu (Nakagawa et al., 2003), and a brGDGTs-based MAAT record from the Shuizhuyang peat deposit (Wang et al., 2017). All these sites are within the region influenced by the EASM (Fig. 5).

It would be expected that temperature changes at higher latitudes would be larger than in the tropical zone during the last deglaciation. However, all the extra-tropical temperature records in the region of influence of the EASM exhibit only a small temperature change during the YD. For example, the high-resolution pollen record from Lake Suigetsu exhibits relatively small summer temperature change during the YD (Nakagawa et al., 2003). Similarly, temperature anomalies estimated from the pollen record from Lake Moon, on the northern limit of the modern EASM, also exhibit minor changes during the YD (Wu et al., 2016). During the YD, the alkenone-inferred summer temperature record in Lake Qinghai decreased by ~2 °C (Hou et al., 2016), which is a much smaller decrease than is observed in Greenland ice cores (Denton et al., 2005; Buizert et al., 2014). The Shuizhuyang peat section (26°46′N, 119°02′E) is located near the Tropic of Cancer, and is sensitive to environmental changes (Wang et al., 2017). The brGDGTs-based MAAT record is characterized by a slight gradual increase in temperature from 12.8 °C to 13.0 °C from about 15 kyr BP, followed by an abrupt decrease in temperature to 10.3 °C (Wang et al., 2017). The temperature changes in the Shuizhuyang peat section are smaller than at Lake Huguangyan, which may support

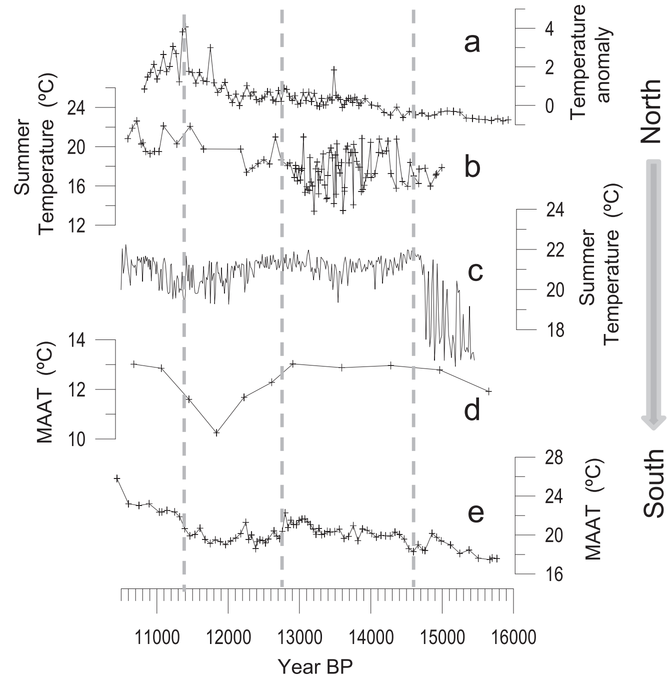

Fig. 5. Comparison of winter-biased temperature in tropical Lake Huguangyan and summer-biased temperature records in extra-tropical regions of East Asia. (a) Temperature anomalies estimated from a pollen record from Lake Moon (Wu et al., 2016). (b) Alkenone-based summer temperature record from Lake Qinghai (Hou et al., 2016). (c) Pollen-based summer temperature record from Lake Suigetsu (Nakagawa et al., 2003); a 250-year adjustment has been used according to Shen et al. (2010). (d) Branched GDGTs-based MAAT record from Shuizhuyang peat section (Wang et al., 2017). (e) MAAT estimated from brGDGTs (this study).

an early suggestion that the brGDGTs produced in lakes are more sensitive to seasonal variations than are brGDGTs in soils (Peterse et al., 2014) and peats.

In summary, the winter-biased temperature changes recorded in tropical Lake Huguangyan are more distinctive than the summer-biased temperature records in the extra-tropical regions of East Asia. This suggests that the decrease in winter temperature during abrupt climatic events was larger than during summer.

4.6. Atmospheric coupling between the Arctic and the tropics

The paleotemperature record from Huguangyan Lake is similar to alkenones-based annual sea surface temperature (SST) records from sediment cores from the tropical South China Sea (Pelejero et al., 1999; Steinke et al., 2008; Shintani et al., 2011) and the western Pacific (de Garidel-Thoron et al., 2007) (Fig. 6). In Huguangyan Lake, the MAAT during the YD and the OD was about 0.7 °C and 2.6 °C colder than during the BA, respectively. These values are slightly higher than the annual SST differences (0.4 °C between the YD and BA, and 1.0 °C between the OD and BA), but are similar to the winter SST difference (0.5 °C between the YD and BA and 2.0 °C between the OD and BA), as recorded in the tropical South China Sea (Steinke et al., 2008). Steinke et al. (2008) noted that the alkenone-based temperature could be weighted towards the winter months because the winter monsoon and the resulting nutrient-rich upper surface waters represent favorable conditions for the growth of alkenone-producing coccolithophores. However, Shintani et al. (2011) suggested that alkenone-based temperature reflects the mean annual SST since satellite observations did not reveal large seasonal variations in chlorophyll concentrations and seasonal temperatures. Opinions differ regarding the main drivers

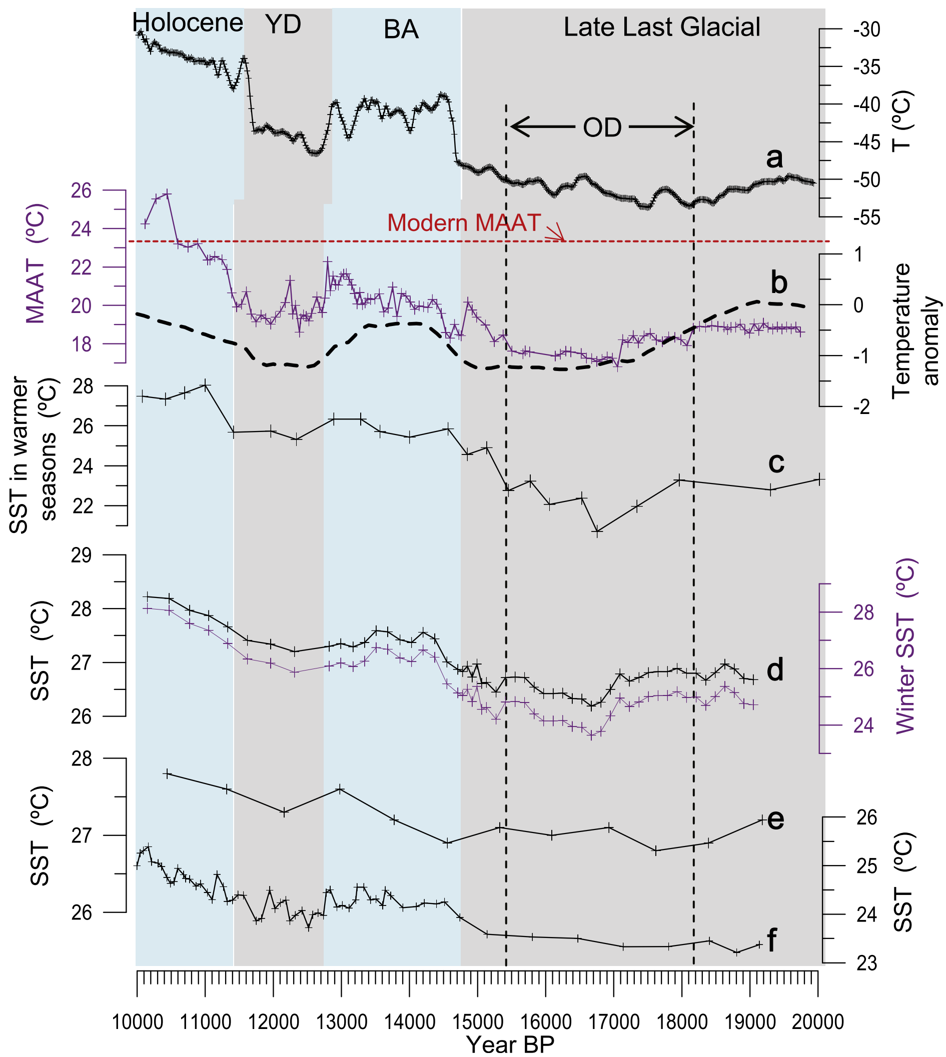

Fig. 6. Comparison of the reconstructed MAAT record with temperature reconstructions from Greenland ice cores and the tropical South China Sea and western Pacific. (a) Greenland $\delta^{15}N$-based temperature reconstruction (average of NEEM, GISP2 and NGRIP) (Buizert et al., 2014). (b) MAAT estimated from brGDGTs (this study) (purple line); temperature difference between the two hemispheres (black dashed line) (Shakun et al., 2012); red dashed line shows the modern MAAT in the study region. (c) TEX86-derived SST record in warmer seasons (Shintani et al., 2011). (d) Alkenones-based annual SST record (black line) and winter SST (purple line) from core MD01-2390 (black line) from the South China Sea (Steinke et al., 2008). (e) Alkenones-based annual SST record from core MD97-2138 from the western equatorial Pacific (de Garidel-Thoron et al., 2007). (f) Alkenones-based annual SST record from core 17,940 from the South China Sea (Pelejero et al., 1999). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

of SST variations in the South China Sea, such as the winter monsoon (Steinke et al., 2008), summer monsoon (Oppo and Sun, 2005), ENSO variability (Rosenthal et al., 2003) and sea level changes (Zhao et al., 2006). Nevertheless, a similar pattern can be observed within the time series from tropical Lake Huguangyan and the tropical ocean (Fig. 6). The brGDGTs record from Lake Huguangyan provides robust evidence for winter-biased temperature changes due to its monomictic nature. A previous diatom-based winter monsoon proxy suggested a strong winter monsoon during the YD (13.0–11.7 kyr BP) in Lake Huguangyan (Wang et al., 2012). The distinct temperature decrease observed in this study and the winter monsoon record support the occurrence of severe winter conditions during the YD.

It has been suggested that the abrupt temperature changes recorded in Greenland ice cores during the YD were linked to strong seasonality dominated by very cold winter temperatures (Denton et al., 2005; Buizert et al., 2014). Within the limits of the dating uncertainties, the synchroneity of temperature variations between tropical Asia and the Arctic could be the result of a common pattern of climatic variability on a large spatial scale (Fig. 6). The Intertropical Convergence Zone (ITCZ) plays an important role in regulating climate variability through the exchange of water vapor and energy between the two hemispheres (Haug et al., 2001; Chiang and Bitz, 2005; Schneider et al., 2014). On longer timescales, the shift of the ITCZ is coupled with numerous extra-tropical factors such as solar insolation, cross-equatorial atmospheric energy transport, polar ice cover, SST and various patterns of atmospheric circulation. The temperature gradient between the two hemispheres may be the major factor controlling the shift of the ITCZ (Shakun et al., 2012). Fig. 6 compares the temperature record from Lake Huguangyan with the temperature difference between the two hemispheres (Shakun et al., 2012) and there is a clear similarity. Assuming that the mean ITCZ shifted by 1° latitude during the latest part of the last glacial, as previously suggested (McGee et al., 2014), the temperature change in July would be only 0.3 °C, based on the modern temperature gradient in China (0.3 °C in July per degree of latitude) (Liu, 2010). Thus, the migration of the ITCZ is insufficient to explain the large temperature changes observed in Huguangyan Lake.

The Asian winter monsoon is the most active and powerful circulation system in the Northern Hemisphere winter. Cold surges (cold waves) have been proposed as a surrogate for winter monsoon strength (Chen et al., 1991). They originate from anticyclonic outflow over Siberia and the polar regions (Chen et al., 1991; Ou et al., 2015). Modern instrumental observations indicate that a cold surge event is often accompanied by a huge temperature decrease (within less than one week), often exceeding 8–18 °C in southern China (Chen et al., 1991). Additionally, historical documents in tropical China recorded more cold surges (extreme cold winter events such as heavy snowfall and frozen rivers) during the Little Ice Age in the tropical plains (Chu et al., 2002). This constitutes strong evidence for powerful cold surges since phenomena such as frozen rivers and snowfall cannot occur in tropical plain areas, except for China. We speculate that cold surges were more frequent during the YD and the OD than during the Little Ice Age, because the expansion of the Siberian High and polar air outbreaks would be favored by the development of cold air surges over East Asia.

In addition to the shutdown of the North Atlantic Conveyor acting as a trigger for abrupt cooling events, we suggest that the winter monsoon (especially cold surges) could play an important role in the rapid transmission of the temperature signal from the Arctic to the tropics, which was then transferred to the Southern Hemisphere via the migration of the ITCZ.

5. Summary

We have obtained a calibrated brGDGTs-based temperature record spanning the last deglaciation from Lake Huguangyan in tropical South China. The record is weighted towards winter since the lake is monomictic and winter mixing enhances nutrient transport from the lake bottom to the entire water column, greatly promoting biological productivity.

The reconstructed MAAT during the OD and YD was 17.8 °C and 19.8 °C, which was about 5.6 °C and 3.6 °C colder than the modern mean annual air temperature (23.4 °C), respectively. The distinct temperature decrease observed in this study, and in previous diatom-based winter monsoon records, indicates a strong winter monsoon during the YD.

The winter-biased temperature changes observed in tropical Lake Huguangyan are more distinctive than summer temperature records from extra-tropical regions of East Asia. This implies that the temperature decreases observed during abrupt climatic events were mainly a winter phenomenon.

Within the limits of the dating uncertainties, the winter-weighted temperature variations in tropical Lake Huguangyan were temporally associated with the winter-dominated temperature evolution of Greenland. In addition to oceanic teleconnection mechanisms such as the AMOC, we propose that the winter monsoon (especially cold surges) could have played an important role in the rapid transmission of the temperature signal from the Arctic to the tropics, which was subsequently transferred to the Southern Hemisphere via the migration of the ITCZ. Thus, our study may support the hypothesis that abrupt climate change is mainly a winter phenomenon.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.quascirev.2017.10.014.

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