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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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ABSTRACT

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.

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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 δ^{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 δ^{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 δ^{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 anti-phased 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

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