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Biogeochemical evidence of Holocene East Asian summer and winter monsoon variability from a tropical maar lake in southern China

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A B S T R A C T

Lake Huguangyan (21°9′ N, 110°17′ E), a maar lake located near the South China Sea, can provide valuable sedimentary data regarding past changes of the East Asian monsoonal system. Here, we used the proxies of TOC, $\delta^{13}C_{org}$, $\delta^{15}N$, and leaf wax *n*-alkane $\delta^{13}C$ values ($\delta^{13}C_{wax}$) to reconstruct the lake conditions, which, in turn, revealed patterns in monsoonal changes during the Holocene. Two distinct patterns of proxy changes were identified in the sedimentary profile. A marked shift in the $\delta^{13}C_{wax}$ value at ~9.2 ka (thousand years ago) suggests the abrupt disappearance of C_4 plants, signaling the enhancement of East Asian summer monsoon (EASM). Between 9.2 and 1.8 ka, a nearly pure C_3 terrestrial ecosystem was present, with the climax at ca 7–6 ka. After ca 3 ka, fewer tropical species and a reappearance of C_4 plants at 1.8 ka indicate a weakened EASM in the late Holocene. The TOC concentration and $\delta^{15}N$ value proxies appear to be associated with lake aquatic production and upwelled nutrient supply and utilization, which are modulated by, and thus indicative of, the strength of the East Asian winter monsoon (EAWM). The two EAWM records suggest a weakening trend from the early to late Holocene, with the most significant transition at ~6 ka; thus, the EAWM trend was broadly in-phase with that of the EASM. However, the marked EASM intensification at 9.2 ka occurred within the period of a strong EAWM between 10.5 and 6 ka and lagged the monsoonal enhancement as inferred from the Dongge Cave $\delta^{18}O$ values. Our EASM records displays an overall arid-wet-arid pattern, which is in-phase with the hydrological variability in tropical Australia and anti-phase with that in the outer-tropical Andes. These phase relationships might be linked to changes in the thermal state of the tropical Pacific during the Holocene.

1. Introduction

Variations in the East Asian monsoon during the Holocene have been extensively studied during the past several decades based on proxy data obtained from various sedimentary records. These studies have been prompted in part by the large population affected by the East Asian monsoon and the alarming rate of the current global climate change. During recent years, there have been several attempts to reconstruct the Holocene history of the East Asian monsoon by compiling and synthesizing published proxy records that are widely distributed in China. These records, however, have displayed inconsistent trends and thus have produced contradictory histories. For example, An et al. (2000) proposed a time-regression hypothesis in which the East Asian summer monsoon (EASM) maximum displayed a trend of southeastward retreat as the extent of summer insolation declined throughout the Holocene. However, this time-regression hypothesis is not supported by numerous subsequent high-resolution studies, as reviewed by Zhao et al. (2009) and Zhang et al. (2011), who suggested a broadly synchronous climatic history across the monsoon region. Nevertheless, an updated perspective of EASM diachronity presented by Ran and Feng (2013) deemed that the strength of the EASM had

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gradually shifted northward during the early Holocene and southward during the late Holocene. The phase relationship between the EASM and the Indian summer monsoon (ISM) is another focus of debate, with distinct viewpoints indicating a generally in-phase (Herzschuh, 2006) relationship and an anti-phase (Wang et al., 2010) relationship between the two monsoonal systems. The reasons for these different opinions are complex, but one reason may be partly associated with the lack of relatively high-resolution tropical monsoon records extending back to at least the early Holocene in southernmost China, which is closest to the moisture source, i.e., the South China Sea (SCS) and adjacent western tropical Pacific.

The East Asian winter monsoon (EAWM), the winter counterpart of the EASM, is the atmospheric flow over East Asia that originates in the Siberian High centered in Mongolia and northeastern Siberia. Past changes in the EAWM have been inferred mainly from grain size records spanning orbital and millennial time scales from the Chinese Loess Plateau (e.g., An et al., 1991; Liu and Ding, 1998; Porter and Zhou, 2006). Many such records from the Holocene indicate a strengthening of the EAWM over time from one of low intensity during the warm early Holocene to one of high intensity during the cool late Holocene (Yang and Ding, 2008). This trend is also suggested by records of Ti concentration, total organic carbon (TOC) concentration and magnetic susceptibility from Lake Huguangyan (HGY), a tropical lake in southern China (Yancheva et al., 2007). However, an opposite trend in the EAWM during the Holocene, i.e., a weakening EAWM from the early to late Holocene, has been recently proposed based on records of diatom assemblages in the same lake (Wang et al., 2012). Reconstructions of the EAWM based on spatial gradients in sea surface temperatures (SSTs) in the SCS (Steinke et al., 2010, 2011; Huang et al., 2011) also support a stronger EAWM during the early Holocene.

Thus, it appears that high-resolution records from tropical East Asia may provide key evidence regarding the evolution of both the EASM and EAWM. Lake HGY is an ideal location for obtaining such records and has become a favored area for such studies by many paleoclimatologists. Until now, only a few sets of sediment cores have been collected for such studies. The first set was collected in 1997 by a team from GeoForschungsZentrum Potsdam and the Chinese Academy of Sciences (Mingram et al., 2004) and was the basis for developing numerous conclusions regarding climate change since the last deglaciation (e.g., Liu et al., 2000; Mingram et al., 2004; Wang et al., 2007; Yancheva et al., 2007; L Wang et al., 2008, 2012). However, as noted by Wu et al. (2012), those studies are all based on a poorly constrained age model of the Holocene sediments that lacks good ^{14}C age control for the period between 8400 and 3800 yrs before present (BP), which is a critical transition period in Holocene climate evolution. By providing a continuous, well-constrained, high-resolution ^{14}C age record from a second set of cores, Wu et al. (2012) pinpointed a marked transition in the TOC level, Rb/Sr ratio and magnetic susceptibility at 6080 yrs BP; the previous age model would have assigned this transition a date of 7800 yrs BP. In addition to these age discrepancies, there are also opposing opinions regarding whether certain environmental proxies in the lake sediment are robust indicators of the EASM or EAWM. The reliability of Ti concentration, TOC level, and magnetic susceptibility as indicators of the EAWM (Yancheva et al., 2007) has been questioned (Zhou et al., 2007, 2009; Wu et al., 2012; Shen et al., 2013), and these trends have instead been interpreted as reflecting the EASM (Wu et al., 2012). This inconsistency in proxy interpretations thus prevents a clear understanding of the phase relationship between the EASM and EAWM.

In this study, records from a new set of cores with well-constrained ^{14}C age determinations from Lake HGY were analyzed. Novel proxies were studied, including stable carbon and/or nitrogen isotope values in bulk samples and higher plant leaf wax *n*-alkanes. Using these proxies, we attempted to develop a better understanding of the evolution of both the EASM and EAWM during the Holocene from a single set of sediment cores. On this basis, a mechanism of variations in the EASM mediated by the El Niño-Southern Oscillation (ENSO) is proposed.

2. Geographical setting, sediment cores, and chronology

Lake HGY (21°9′ N, 110°17′ E, Fig. 1) is a volcanic crater lake (i.e., maar) located near the southernmost tip of mainland China and only 4 km from the present coastline of the SCS (Fig. 1). At present, the lake has a surface area of 2.25 km^2 and a catchment area of 3.2 km^2, with a maximum water depth of ~20 m in the south-central region. The lake is bilobate with a submerged north-south ridge in the south-central area.

The site is directly affected by the monsoon climate, which exhibits seasonal changes in atmospheric circulation and precipitation. During the summer months, i.e., from April to October, the EASM brings a large quantity of rain to this area, accounting for 90% of the mean annual precipitation of ca 1600 mm. In addition, high temperatures and weak winds promote thermal stratification in the lake water column, resulting in low nutrients and phytoplankton levels (Zhang et al., 2008; Wang et al., 2012). During the winter months, i.e., from November to March, a strong cold and dry EAWM from the north and northeast prevails and breaks up the thermal stratification of the lake, causing nutrient-rich bottom water to mix with surface water and thereby leading to an increased abundance of phytoplankton (Zhang et al., 2008; Wang et al., 2012).

In 2009, three vertical cores, designated HGY-2, HGY-6 and HGY-7 and located several meters apart, were collected from the lake bottom below water depths of ~10 m using a modified Livingstone piston corer (Yang et al., 2012). Cores HGY-2 and HGY-6 measured 1.67 and 1.89 m in length, respectively. A few tens of centimeters of the upper sediments of the two cores were lost due to their high water content. Core HGY-7 was obtained beginning at a depth of ~1.5 m below the lake bottom and was 3.68 m long. These three cores were split, and one half from each core was continuously sampled at 1-cm intervals in the laboratory for magnetic susceptibility analysis. The magnetic susceptibility features were clear and

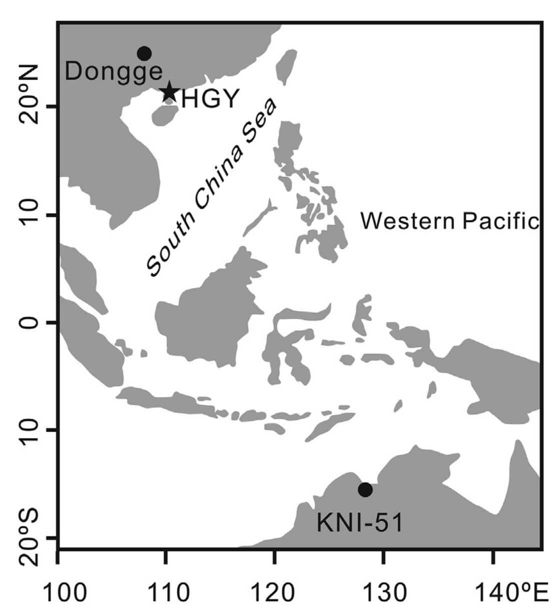

Fig. 1. Location of Lake Huguangyan.