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Transition from a warm and dry to a cold and wet climate in NE China across the Holocene

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ABSTRACT

Northeast (NE) China lies in the northernmost part of the East Asian Summer monsoon (EASM) region. Although a series of Holocene climatic records have been obtained from lakes and peats in this region, the Holocene hydrological history and its controls remain unclear. More specifically, it is currently debated whether NE China experienced a dry or wet climate during the early Holocene. Here we reconstruct changes in mean annual air temperature and peat soil moisture across the last ∼13,000 year BP using samples from the Gushantun and Hani peat, located in NE China. Our approach is based on the distribution of bacterial branched glycerol dialkyl glycerol tetraethers (brGDGTs) and the abundance of the archaeal isoprenoidal (iso)GDGT crenarchaeol. Using the recently developed peat-specific $MAAT_{peat}$ temperature calibration we find that NE China experienced a relatively warm early Holocene (∼5–7 °C warmer than today), followed by a cooling trend towards modern-day values during the mid- and late Holocene. Moreover, crenarchaeol concentrations, brGDGT-based pH values, and the distribution of 6-methyl brGDGTs, all indicate an increase in soil moisture content from the early to late Holocene in both peats, which is largely consistent with other data from NE China. This trend towards increasing soil moisture/wetter conditions across the Holocene in NE China records contrasts with the trends observed in other parts of the EASM region, which exhibit an early and/or mid-Holocene moisture/precipitation maximum. However, the Holocene soil moisture variations and temperature–moisture relationships (warm–dry and cold–wet) observed in NE China are similar to those observed in the core area of arid central Asia which is dominated by the westerlies. We therefore propose that an increase in the intensity of the westerlies across the Holocene, driven by increasing winter insolation, expanding Arctic sea ice extent and the enhanced Okhotsk High, caused an increase in moisture during the late Holocene in NE China.

1. Introduction

Climate in northeastern (NE) China is influenced by the interplay of different atmospheric circulation patterns, predominantly the Asian monsoon system and the northern-part of the Westerlies. The climate evolution in the region since the last deglacial period has been reconstructed using various types of paleoclimatic archives, such as lake sediments (e.g., Stebich et al., 2015; Zhou et al., 2016), peats (e.g., Zhou et al., 2010; Zheng et al., 2017), and speleothem oxygen isotope records (e.g., Wu et al., 2011). Several of these paleoclimatic studies have suggested that the climate of this region since the last deglaciation differed from that of other East Asian monsoon regions (e.g., Zhou et al., 2010; Stebich et al., 2015; Zheng et al., 2017).

Although these paleoclimate studies have improved our understanding of Holocene climate and environmental change, the various reconstructed patterns of hydrological change in NE China are inconsistent. For example, using *n*-alkane ratios in peat, Zhou et al. (2010) suggested that NE China was characterized by a dry early Holocene (∼10.5 to 6 ka), attributed to enhanced evaporation caused by high sea surface temperatures (SSTs) from the nearby Japan Sea, and a wet late Holocene (after ∼6 ka). This

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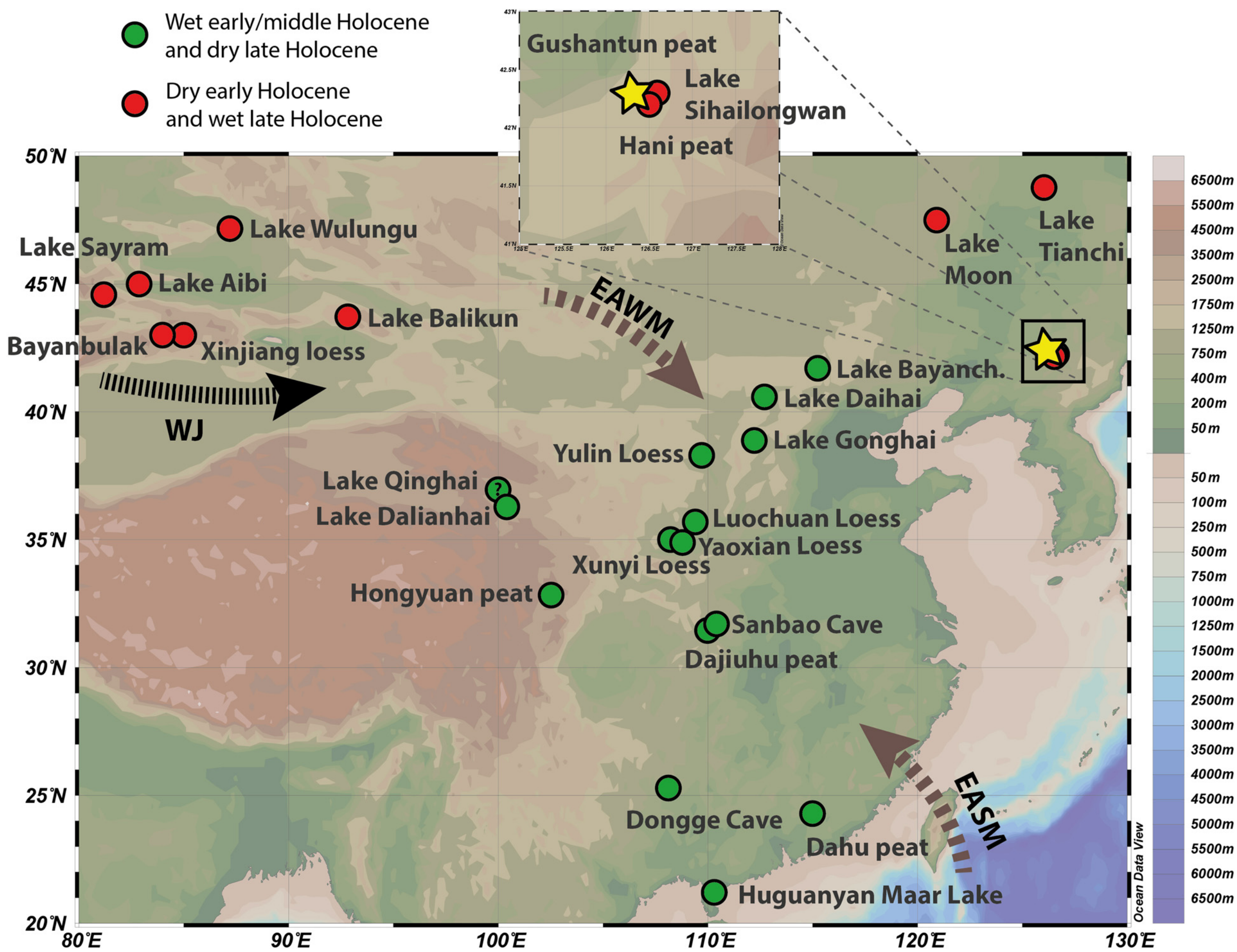

Fig. 1. Location of the Gushantun peat (yellow star) and other sites in arid central Asia and the East Asian Monsoon region: Huguangyan Maar lake (Wang et al., 2007); Dahu peat (Zhou et al., 2004); Dongge Cave (Dykoski et al., 2005); Dajiuhu peat (Zhu et al., 2010); Sanbao Cave (Wang et al., 2008); Hongyuan peat (Zheng et al., 2007); Yaoxian Loess (Zhao et al., 2007); Xunyi Loess (Stevens et al., 2008); Luochuan Loess (Lu et al., 2013); Yulin Loess (Lu et al., 2013); Lake Dalianhai (Cheng et al., 2013); Lake Qinghai (Shen et al., 2005; An et al., 2012; Wang et al., 2014); Lake Gonghai (Chen et al., 2015); Lake Daihai (Xiao et al., 2004); Lake Bayanch. (Bayanchagan, Jiang et al., 2006); Lake Tianchi (Zhou et al., 2016); Lake Moon (Liu et al., 2010); Lake Sihailongwan (Stebich et al., 2015); Hani peat (Zhou et al., 2010); Xinjiang loess (Chen et al., 2016); Bayanbulak (Long et al., 2017); Lake Balikun (Tao et al., 2010); Lake Aibi (Wang et al., 2013); Lake Sayram (Jiang et al., 2013); Lake Wulungu (Liu et al., 2008). Also shown are the dominant atmospheric circulation systems: the EASM-East Asian summer monsoon, EAWM-East Asian winter monsoon, WJ-Westerly jet. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

is consistent with pollen records from lake sediments from the Sihailongwan Maar and Tianchi lake (see compilation of Fig. 1) that indicate wettest conditions after 5 ka (Stebich et al., 2015; Zhou et al., 2016). However, a climatic evolution from a dry early Holocene to a wet late Holocene is unexpected, because the intensity of the EASM is controlled by local summer insolation, with high insolation warming the continent and leading to a stronger EASM (Wang, Y. et al., 2005; Wang, P.X. et al., 2005). Summer insolation was highest during the early Holocene and decreased since then (Berger and Loutre, 1991). Indeed, there are other records from the region that indicate a wet early Holocene and dry late Holocene (Li et al., 2017), more in-line with the expected evolution of the EASM based on the local insolation. The contrasting response recorded in different proxies and in different regions indicates that the climatic evolution of NE China and especially the EASM across the Holocene remains poorly constrained. This highlights a fundamental gap in our understanding of the processes and mechanisms that drive the expression of the Monsoon in NE China.

Over the last decade, peats have become an important archive for the reconstruction of terrestrial climate change in Asia (e.g., Barber et al., 2003; Xie et al., 2004; Hong, Y.T. et al., 2005; Zheng et al., 2007, 2015, 2017). The rate of peat accumulation and water table position are sensitive to changes in precipitation and temperature (Barber et al., 2000; Ise et al., 2008). Peat deposits are widespread in NE China and can extend back into the last deglaciation, representing the potential to constrain the deglacial evolution of climate. Previous peat-based palaeoclimate studies in NE China have focused predominantly on the Hani peatland using a range of proxies including n-alkane δD and δ^{13}C values (Seki et al., 2009; Yamamoto et al., 2010), peat cellulose δ^{13}C and δ^{18}O records (Hong, Y.T. et al., 2005; Hong, B. et al., 2009), compositional changes in n-alkanes, n-alkanoic acids and n-alkanols (Zhou et al., 2010), n-alkan-2-one distributions (Zheng et al., 2011), glycerol dialkyl glycerol tetraethers (GDGTs) (Zheng et al., 2017), and macrofossil analysis (Schröder et al., 2007). However, biomarker records are currently lacking from other peats in NE China that span the deglaciation such as the Gushantun peat deposits. Although pollen and grain sizes have been used to reconstruct Holocene climate and vegetation changes in the Gushantun peat (Liu, 1989; Zhao et al., 2015; Li et al., 2017), the temperature and paleohydrological variations in this peatland during the Holocene are currently unknown. To provide new information on the paleoclimate history of NE China, and dynamics of the EASM, our study employs high temporal resolution (∼100–200 year resolution) paleoclimatic proxies