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Holocene cyclic climatic variations and the role of the Pacific Ocean as recorded in varved sediments from northeastern China

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ABSTRACT

We present an *n*-alkane and compound-specific carbon isotope record of the past 9 ka from the annually laminated sedimentary sequence of Lake Xiaolongwan, northeastern China. The *n*-alkane distribution suggests that Lake Xiaolongwan has undergone a shift from an oligotrophic state with low algal production and little emergent/submerged macrophytes in the early Holocene, to a eutrophic state with high algal production and abundant emergent/submerged macrophytes since the middle Holocene. The pattern of variation observed in the biomarker proxies ACL (the *n*-alkane average chain length), Paq (aquatic macrophyte versus aquatic macrophyte and terrestrial plant ratio), and LPTP (lake productivity/terrigenous organic production) is throughout the record similar to that of the total organic carbon. The variation of compound-specific carbon isotopic values in the middle- and short-chain alkanes was mainly regulated by lake productivity and the accumulating organic pool through time. In this forested region, where the vegetation is dominated by C_3 plants, the long-chain *n*-alkanes (C_{27}–C_{31}) are predominantly derived from leaf wax lipids. The compound-specific $\delta^{13}C_{27-31}$ value is sensitive to effective precipitation, and therefore represents a useful indicator of regional monsoonal precipitation. Spectral analysis on the $\delta^{13}C_{27-31}$ time series reveals significant periodicities of 87–89, 205–212, 1020–1050 and 1750–2041 years. On the centennial timescale, the quasi-periodicities around 88 and 210 years suggest a strong link between solar activity and monsoon rainfall. The millennial monsoon cycle in northeastern China is associated with sea surface temperature (SST) variations in two active centers of the summer monsoon, the western Pacific Subtropical High (WPSH) and the Okhotsk High. Increasing SST in the subtropical sea may cause a northwards shift of the WPSH, which extends the monsoon rain band (Meiyu) to northeastern China, and thus increasing rainfall in that region. Meanwhile, decreasing SST in the Okhotsk Sea may strengthen the Okhotsk high, bringing more moisture into northeastern China. We suggest that the Pacific Ocean is a main regulator for summer monsoon rainfall in northeastern China at present and at different time scales during the Holocene.

1. Introduction

A number of paleoclimatic studies highlighted the importance of cyclic climate variations because they may be intrinsic to the climate system (Bond et al., 1997; Bianchi et al., 1999; Yu et al., 2003). If such climatic variations are demonstrated, it would greatly improve our understanding the climate system response to external forcings and anthropogenic influences, and project future climate change.

In the Holocene, one of the most distinctive cycle is the millennial-scale climatic variation recognized in the original ice-rafted debris record from the North Atlantic regions, although it is not perfectly periodic with cycles around 1470 ± 500 years (Bond et al., 1997), and not well replicated in other independent records of ice-rafting (Moros et al., 2004; Fisher et al., 2006; Andrews et al., 2009). An increasing number of Holocene proxy records have demonstrated that the millennial-scale climate change is a global phenomenon, which is not limited to the North Atlantic regions and the Northern Hemisphere (Yu et al., 2003; Yuan et al., 2004; Wang et al., 2005; Darby et al., 2012; Murakami et al., 2012), but also extends to the Southern

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Hemisphere (Holmgren et al., 2003; Rosqvist and Schuber, 2003; Baker et al., 2005; Santos et al., 2013).

In the Asian monsoon area, evidence of cyclic monsoonal oscillations has been mainly derived from the $\delta^{18}O$ records of well-dated stalagmites (Dykoski et al., 2003; Yuan et al., 2004; Wang et al., 2005; Fleitmann et al., 2007), a few lacustrine sediment records (Schettler et al., 2006; Yu et al., 2006; An et al., 2012) and aeolian–paleosol profiles (Porter and Weijian, 2006). These observed oscillations often have been linked with the North Atlantic climate. However, there are noticeable discrepancies in the timing and magnitude of the variations in monsoon rainfall or effective moisture among the different climatic regions (Xiao et al., 2004; Hong et al., 2005; Schettler et al., 2006; Chen et al., 2008; Zhang et al., 2011; Zhao and Yu, 2012). For example, stalagmite records in central and southeastern China (Dykoski et al., 2003; Yuan et al., 2004; Wang et al., 2005) are characterized by a humid climate in the early Holocene, and a gradual weakening monsoon that broadly follows the reduction in precession-driven summer insolation in the Northern Hemisphere (Wang et al., 2005). However, in northern China lacustrine records indicate that the early Holocene was characterized by dry conditions, whereas the late Holocene was moderately wet under the influence of the East Asian monsoon-dominated climate (Xiao et al., 2004; Chen et al., 2008).

In their review of global paleoclimatic archives, Wanner et al. (2011) argued that these apparently cyclic variations were not strictly regular, and that one single process could not explain the complex spatiotemporal pattern observed in the Holocene. These discrepancies may be partly due to the uncertainties in proxy interpretation and dating. For example, while the Chinese stalagmites have been recognized as valuable paleoclimatic archives for tracking monsoon variability in continental settings, there is an ongoing debate as to whether the variations of stable oxygen isotopes reflect local monsoon rainfall, monsoon strength, the combined influence of both summer and winter climatic changes, interhemispheric temperature gradients or long-distance air mass signals (e.g., Clemens et al., 2010; Tan, 2013). More independent high-resolution data are needed to verify the sensitivities of the different proxies.

In addition to the uncertainties in proxy records, the spatial complexity of monsoon rainfall makes it too difficult to gain an overall view of monsoon variability during the Holocene. The Asian summer monsoon is the largest monsoon system on Earth, including several subsystems (the Indian summer monsoon, the western North Pacific summer monsoon, the East Asian summer monsoon, and the Northeastern summer monsoon) (Chen et al., 1991; Ding, 1994). For example, the East Asian Summer Monsoon (EASM) consists of the subtropical monsoon (Meiyu) and the tropical monsoon (tropical monsoon trough), physically derived by distinct forcing mechanisms (Ding, 1994). This complexity implies that regional paleomonsoon rainfall might be inconsistent across monsoon dominated Asia. More high-resolution regional climatic data are needed to understand dynamical link between regional response and the Pacific Ocean because it is a major source of water vapor for the Asian summer monsoon.

Here, we report an *n*-alkane and compound-specific carbon isotopic record for the past 9.0 ka derived from the annually laminated sediments of Maar Lake Xiaolongwan, northeastern China. The aims of this study are to track monsoon variability at centennial-to millennial-scale and to understand the dynamic link behind the shifts in regional climate. In addition, this study provides an opportunity to compare the organic-derived signal from lacustrine sediments with the inorganic-derived signal from stalagmite $\delta^{18}O$ records in the same climatic region.

2. Background

2.1. Regional setting and climatology

Our study area is located in northeastern China and is under the influence of the East Asian monsoonal climate (Fig. 1). In summer, subtropical monsoon rainfall (Meiyu in Chinese, Changma in Korean and Baiu in Japanese) is mainly associated with the northward shift of the western Pacific Subtropical High (WPSH) from June to September. Meanwhile, the Okhotsk High (a semi-permanent high pressure zone) forms and intensifies over the Sea of Okhotsk, brings vapor (cold and wet air, the Northeast Monsoon) to northeastern China, contributing to increasing summer precipitation (Wang, 1992). About 60% of the mean annual precipitation of ~770 mm falls between June and August. In winter and spring, the strong winter monsoon and westerlies create favorable conditions for the development or intensification of cyclones and anticyclones resulting in heavy snow and dust storms.

Lake Xiaolongwan (42°18′N, 126°21′E) is a small closed maar lake with a maximum depth of 16 m and a surface area of 0.08 km^2 (Fig. 1). The lake is ice-covered from the end of November to the start of April. The modern vegetation in the catchment is composed of a deciduous broadleaf-conifer mixed forest (canopy coverage >90%) and is dominated by C_3 plants (Sun et al., 2013). Historically, this remote area has suffered little human disturbance, because it was claimed as the birthplace of the Manchu people (the royal family) and a sacred land by the Qing dynasty (AD 1644–1911). Limited forest clearance occurred in the 1970s and 1980s outside the lake catchment. In 1992, the area was established as a national forest park, thus the regional vegetation has been well preserved.

2.2. Previous paleoclimatic studies from maar lakes

Maar lakes have been recognized as ideal sites for the preservation of paleoclimatic archives because of their close morphology, relatively simple hydrological system, annually laminated sediment and a number of proxy records in their sediment (Negendank and Zolitschka, 1993; Zolitschka et al., 2000). The maar lakes in northeastern China have been the subjects of numerous studies focused on paleoclimatic and paleoenvironmental changes (Mingram et al., 2004; Schettler et al., 2006; Chu et al., 2008, 2009; Jiang et al., 2008; Parplies et al., 2008; You et al., 2008; Stebich et al., 2009; Panizzo et al., 2013; Rioual et al., 2013; Wang et al., 2013a; Xu et al., 2014).

Previous independent radiometric dating results (^{137}Cs, ^{210}Pb and AMS ^{14}C) and monthly sediment trap data have demonstrated the annual nature of the laminations in Lake Sihailongwan and Lake Xiaolongwan (Mingram et al., 2004; Schettler et al., 2006; Chu et al., 2008). Dinocyst-dominated varves have been reported in a previous study on Lake Xiaolongwan (Chu et al., 2008). These particular varves consist of a brown-colored dinocyst layer and light-colored mixed layer (plant detritus, diatoms, chrysophyte cysts, and clastics) (Chu et al., 2008). In their study, based on geochemical proxy data (*n*-alkane and compound-specific carbon isotope) and historical documents, Sun et al. (2013) verified that the compound-specific carbon isotopes from long-chain *n*-alkanes (C_{27}–C_{31}) are useful indicators of effective precipitation or drought stress. They also suggested that summer monsoon rainfall in northeastern China might have been regulated mainly by the Pacific Decadal Oscillation (PDO) over the last millennium. Recently, a high-resolution pollen record revealed 500-year climate cycles over the past 5350 years in the Lake Xiaolongwan (Xu et al., 2014). In the neighboring Lake Sihailongwan, a multiproxy record (biogenic silica, geochemical, sediment characteristics and pollen) suggested