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Long-term weakening of the East Asian summer and winter monsoons during the mid- to late Holocene recorded by aeolian deposits at the eastern edge of the Mu Us Desert

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ABSTRACT

The East Asian summer monsoon (EASM) and East Asian winter monsoon (EAWM) are major drivers of environmental conditions in East Asia. However, due to the lack of high-resolution EAWM records, the phase relationship between the EASM and EAWM during the Holocene epoch is still debated. Here, we use magnetic and grain-size measurements from a sequence of aeolian sediments from the eastern edge of the Mu Us Desert to track the history of the EASM and EAWM from 7.5 to 2.5 ka. The results show that both the EASM and EAWM exhibit a similar long-term weakening trend during this interval. In view of the stable glacial boundary conditions and the significantly decreased rates of atmospheric CO_2 rise since the mid-Holocene, we suggest that orbitally-induced insolation was the major cause of the weakening of both the EASM and EAWM. Decreasing summer insolation and increasing winter insolation reduced the thermal contrast between the ocean and the Asian continent in both summer and winter time, resulting in the weakening of both monsoon systems during the mid- to late Holocene.

1. Introduction

The East Asian monsoon (EAM) is an important component of the global atmospheric circulation system, and its location and intensity have a major influence on the climate of China. The East Asian summer monsoon (EASM) brings rainfall and promotes biological activity and pedogenesis, while the East Asian winter monsoon (EAWM) is characterized by strong winds and sandstorms. Loess deposits on the Chinese Loess Plateau (CLP) provide a remarkable record of the EAM up to 22 Ma ago (Guo et al., 2002). Numerous Chinese loess studies have demonstrated that variations in the intensity of the EASM, revealed by magnetic susceptibility measurements and of the EAWM, revealed by grain-size measurements, were anti-phased on glacial-interglacial timescales; and that glacial intervals were characterized by an overall strong EAWM and weak EASM, while interglacial times were characterized by a weak EAWM and strong EASM (e.g. An et al., 1991; Ding et al., 1995; Xiao et al., 1995; Sun et al., 2006b, 2015; Hao et al., 2012). However, due to the lack of high-resolution EAWM records, the phase relationship between the EASM and EAWM during the Holocene is controversial.

For example, Yancheva et al. (2007) proposed an inverse correlation between the EASM and EAWM based on comparison of a record of Ti content (an EAWM indicator) from the sediments of Huguang Maar Lake in coastal southeast China with the oxygen isotope record (an EASM indicator) of stalagmites (e.g. Dykoski et al., 2005) in south China. However, it is unclear whether Ti is transported by the EAWM from the CLP or by hydrological processes within lake catchments (Zhou et al., 2007b). Moreover, based on the use of variations in the relative abundance of two planktonic diatom species as an EAWM proxy, another research from Huguang Maar Lake showed that the EAWM was in-phase instead of anti-correlated with the EASM on an orbital timescale during the Holocene (Wang et al., 2012). Furthermore, many recently published researches supported that the two monsoon systems exhibited synchronous changes during the Holocene. By combining grain-size standard deviation analysis with a transient climate simulation, Li and Morrill (2014) suggested a strong early Holocene EAWM followed by a weakening of EAWM after the mid-Holocene at the southern edge of the Gobi Desert; and this trend was similar to a long-term weakening of the EASM revealed by stalagmite oxygen isotope records (e.g. Dykoski et al., 2005). Grain-size records from the central Yellow Sea of China indicated that the EAWM strength broadly followed the orbitally-derived winter insolation with a similar long-term stepwise decreasing trend as the EASM (Hu et al., 2012b). In the South China Sea (SCS), researchers tracked EAWM activity using various proxies: Mg/Ca ratios of planktonic foraminifers to estimate the

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latitudinal sea surface temperature (SST) gradient (Tian et al., 2010) and the temperature difference between sea surface and thermocline waters (Steinke et al., 2010, 2011), and the alkenone-based west-east SST gradient (Huang et al., 2011). These studies reveal a common trend of long-term decreasing EAWM strength during the Holocene which in-phase with the EASM (Steinke et al., 2010, 2011; Huang et al., 2011). But, there are also some studies showed that the two monsoon systems were neither in-phase nor anti-phase during the Holocene. Based on variations in magnetic properties and grain-size of loess deposits on the CLP, Xia et al. (2014) suggested that the EASM and EAWM were out-of-phase during the Holocene, and that the EASM maximum preceded the EAWM minimum by about 2.8 ka. Research on Hongyuan swamp in the eastern Tibetan Plateau showed that the Asian summer and winter monsoons varied inversely before 5.5 ka BP, but synchronously afterwards (Yu et al., 2011).

In summary, most of the aforementioned researches support the view that the EAWM and EASM were not anti-phased during the Holocene; however, because of the lack of independent EASM proxies, the oxygen isotope record from stalagmites was used as a proxy (Tian et al., 2010; Steinke et al., 2010, 2011; Huang et al., 2011; Wang et al., 2012; Hu et al., 2012b; Li and Morrill, 2014). However, the environmental significance of stalagmite oxygen isotope is debated (Maher, 2008; Clemens et al., 2010; Wang et al., 2014; Liu et al., 2015) and in fact numerous other EASM records are in disagreement with the stalagmite oxygen isotope records. For example, pedogenesis in the CLP (Wang et al., 2014) and in the sandy lands in northern China (Lu et al., 2005, 2013b; Sun et al., 2006a; Mason et al., 2009; Xu et al., 2013; Li et al., 2014) documents an EASM maximum during the mid-Holocene, while stalagmite oxygen isotope records (e.g. Dykoski et al., 2005) record a strongest EASM during the early Holocene. In the present study, we use magnetic and grain-size parameters to reconstruct the EASM and EAWM intensity at the eastern edge of the Mu Us Desert, and use the results to investigate the phase relationship between the two monsoon systems during the mid- to late Holocene.

2. Regional setting

The Mu Us Desert (Fig. 1) is located in the southern Ordos Plateau to the north of the CLP. The desert lies between 37°27.5′–39°22.5′N and 107°20′–111°30′E and covers an area of about 32,100 km^2. The altitude ranges from 1200–1600 m above sea level (ASL). Thin, undulating sand sheets, fixed dunes, and semi-fixed dunes are typical landforms. Sandy material in the Ordos Plateau is mainly derived from the Cretaceous and the Jurassic bedrock and from early Quaternary lacustrine and alluvial sediments (Wang et al., 2011). The Mu Us Desert is located in the northwestern frontier of the modern boundary of the EASM, and is classified as a temperate semi-arid climatic region. The mean annual temperature is 6–9 °C and the mean annual precipitation is 250–420 mm, with about 70% of monsoonal rainfall occurring in summer (Xu et al., 2013). Northwesterly winds prevail in winter and spring accompanying frequent dust storms, while southeasterly winds prevail in summer coupled with abundant rainfall (Jia et al., 2015). The region is assigned to the steppe zone, and is also one of the typical regions suffering from severe aeolian desertification in China (Wang et al., 2011).

3. Materials and methods

3.1. Section and sampling

The Jinjie section (38°44.594′N, 110°10.044′E, and 1159 m ASL) is located in the second terrace of the Tuiwei River, one of the tributaries of the Yellow River, at the eastern edge of the Mu Us Desert (Fig. 1). Landform around the section is gentle. There are many hills and gullies on the east of this area. This area is sensitive to northwesterly EAWM and conductive to aeolian sand deposition due to the blocking effect of the hills. The section is within a fixed dune, and the vegetation coverage is approximately 70–80%, consisting mainly of *Artemisia ordosica* and *Salix psammophila* (Liu et al., 2014). The 7.4-m-thick section consists of five aeolian sand layers, three palaeosols, one weakly-developed

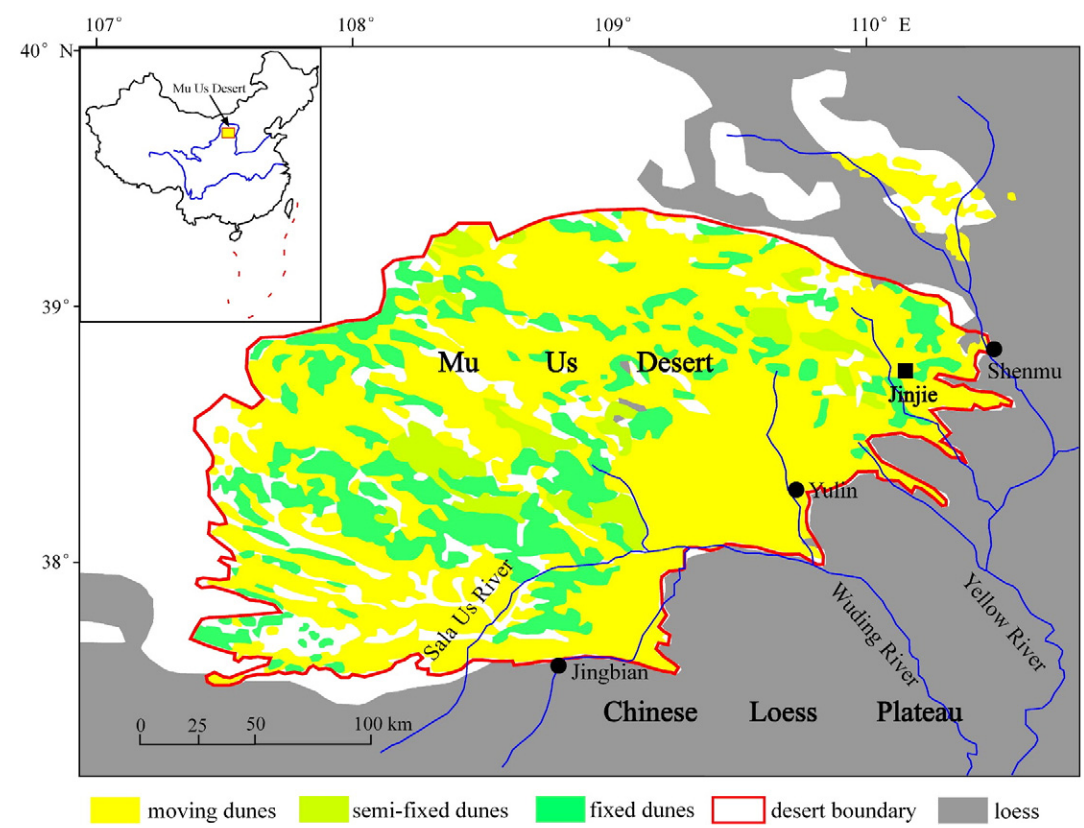

Fig. 1. Location of the Mu Us Desert and the Jinjie section (modified from Xu et al., 2013).