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Late Holocene anti-phase change in the East Asian summer and winter monsoons

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ABSTRACT

Changes in East Asian summer and winter monsoon intensity have played a pivotal role in the prosperity and decline of society in the past, and will be important for future climate scenarios. However, the phasing of changes in the intensity of East Asian summer and winter monsoons on millennial and centennial timescales during the Holocene is unclear, limiting our ability to understand the factors driving past and future changes in the monsoon system. Here, we present a high resolution (up to multidecadal) loess record for the last 3.3 ka from the southern Chinese Loess Plateau that clearly demonstrates the relationship between changes in the intensity of the East Asian summer and winter monsoons, particularly at multicentennial scales. At multimillennial scales, the East Asian summer monsoon shows a steady weakening, while the East Asian winter monsoon intensifies continuously. At multicentennial scales, a prominent ~700–800 yr cycle in the East Asian summer and winter monsoon intensity is observed, and here too the two monsoons are anti-phase. We conclude that multimillennial changes are driven by Northern Hemisphere summer insolation, while multicentennial changes can be correlated with solar activity and changing strength of the Atlantic meridional overturning circulation.

1. Introduction

The East Asian monsoon system includes the warm-moist southeasterly East Asian summer monsoon (EASM) and the cold-dry northwesterly East Asian winter monsoon (EAWM) (Fig. 1a), which both show great variability at different timescales (e.g. orbital, millennial, centennial, decadal) and play a role in the development of the economy, society, biology etc. of East Asia (Wang, 2006). Changes in past EASM and/or EAWM intensity have been reconstructed from a variety of palaeoclimate archives, including loess (e.g. An et al., 1991a, 1991b; Ding et al., 2002; Hao et al., 2012; Sun et al., 2012; Lu et al., 2013; Xia et al., 2014; Li and Morrill, 2015), deserts (e.g. Yang et al., 2011; Yang et al., 2013; Long et al., 2017), lake sediments (e.g. Yancheva et al., 2007; Liu et al., 2009; An et al., 2012; Wang et al., 2012; Chen et al., 2015), cave speleothem (e.g. Wang et al., 2005; Wang et al., 2008; Zhang et al., 2008; Cheng et al., 2016), ocean sediments (e.g. Tian et al., 2010; Steinke et al., 2011; Zheng et al., 2014; Zhang et al., 2015) etc., which is important for the understanding of present and future monsoon climate (Wang, 2006). At present, it is widely accepted that the EASM and EAWM intensity are anti-phase at both orbital- and millennial-scales beyond the Holocene (e.g. during the last glacial-interglacial cycle), as is well documented by loess on the Chinese Loess Plateau (CLP) and cave speleothem in southern China (e.g. An et al., 1991a, 1991b; Ding et al., 2002; Wang et al., 2008; Hao et al., 2012; Sun et al., 2012; Cheng et al., 2016; Maher, 2016). Orbital-scale EASM and EAWM variability can be mainly attributed to changes in orbitally-induced Northern Hemisphere summer insolation (NHSI) (Ding et al., 2002; Hao et al., 2012; Cheng et al., 2016), and changes of the Atlantic meridional overturning circulation (AMOC) strength are suggested to be potentially responsible for last glacial millennial-scale changes (Wang et al., 2008; Sun et al., 2012).

Although changes of the EASM intensity at various timescales during the Holocene have been well reconstructed (e.g. Wang et al., 2005; Zhang et al., 2008; Liu et al., 2009; Tan et al., 2011; An et al., 2012; Lu et al., 2013; Chen et al., 2015), EAWM records are still sparse. The existing EAWM records (e.g. Yancheva et al., 2007; Liu

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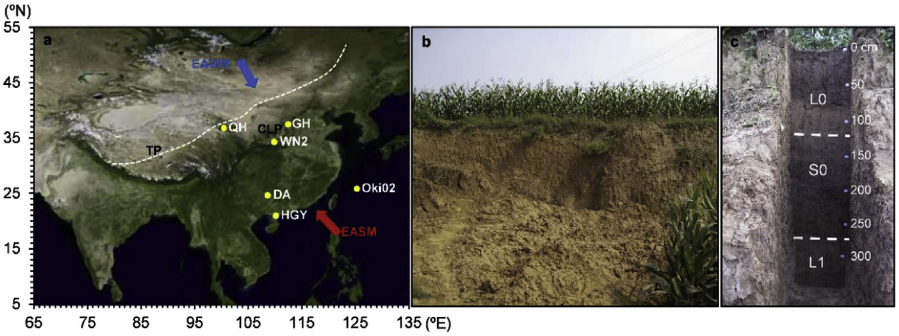

Fig. 1. Site locations and Weinan loess section. (a) Location of Weinan section (this study) and other sites mentioned in the text, and atmospheric circulation in East Asia. QH-Qinghai (An et al., 2012), GH-Gonghai (Chen et al., 2015), DA-Dongge (Wang et al., 2005), HGY-Huguangyan (Yancheva et al., 2007), Oki02-Okinawa02 (Zheng et al., 2014), WN2-Weinan (this study), EASM-East Asian summer monsoon, EAWM-East Asian winter monsoon, CLP-Chinese Loess Plateau, TP-Tibetan Plateau. The white dashed line is the landward limit of the modern EASM front. The map is redrawn from Mapworld (http://en.tianditu.com/). (b) Weinan section weathered outcrop. (c) Fresh sampling pit at Weinan, with depth and stratigraphic division also indicated. The white dashed lines are the boundaries of L1/S0 and S0/L0. The uppermost 190-cm loess is focused upon in this study.

et al., 2009; Tian et al., 2010; Steinke et al., 2011; Wang et al., 2012; Xia et al., 2014; Zheng et al., 2014; Li and Morrill, 2015; Yan et al., 2015; Zhang et al., 2015; Wen et al., 2016) are mostly based on non-aeolian deposits and are always controversial. Great differences were observed in previous studies of EAWM intensity changes and forcing mechanisms during the Holocene, and relationships between EASM and EAWM have been variously described as in-phase, anti-phase and out-of-phase at different timescales. Thus, robust high-resolution EAWM records are required to understand the phase relationship between the EASM and EAWM and their forcing mechanisms.

When compared with other sediments, loess on the CLP provides advantages for exploring the phase relationship between EASM and EAWM. This is because the classic, widely-accepted (An et al., 1991a, 1991b; Ding et al., 2002; Hao et al., 2012; Sun et al., 2012; Lu et al., 2013; Xia et al., 2014; Li and Morrill, 2015; Maher, 2016) proxies used to infer the EASM (e.g. magnetic susceptibility (MS)) and EAWM (e.g. mean grain size (MGS)) intensity can synchronously record the intensity changes in both EASM and EAWM. However, there is still a lack of millennial- and centennial-scale EASM and EAWM records in Chinese loess during the Holocene (Lu et al., 2013; Xia et al., 2014; Li and Morrill, 2015), due to the typically low-resolution of records, coupled with limited chronology, possible disturbance by human beings, and biologic activities etc. (Stevens et al., 2006). The existing records show both in-phase (Li and Morrill, 2015) and out-of-phase (Xia et al., 2014) relationships, based on loess in the western and southern CLP respectively.

Reconstruction of past EASM and EAWM changes during the late Holocene (e.g. since ~3 ka) is particularly important for understanding short timescale (e.g. centennial, decadal) monsoon dynamics, and is significant for prediction of monsoon changes in the future. Meanwhile, palaeomonsoon records are significant for interpreting evolution of human activity, culture etc. in East Asia. As mentioned above, during the late Holocene, the EASM intensity changes revealed from different archives are relatively clear, and high-resolution EAWM records, particularly based on loess on the CLP, are difficult to obtain but are much needed. In this study, based on loess from the Weinan site in the southern CLP, considering the dust accumulation rate (DAR) changes and loess resolution, we focus on the late Holocene (the last ~ 3.3 ka) record to reveal EASM and EAWM intensity changes, and their phases and dynamics at multimillennial- and multicentennial-scale.

2. Study area

Situated at the southern margin of the CLP, the Weinan loess section (WN2, 34°24′54.85″N, 109°33′44.18″E, 646 m a.s.l.) is located at the center of a flat tableland ("Dong Yuan" in Chinese), which is approximately 10 km from east to west and 20 km from south to north (Fig. S1b). To the south of the "Dong Yuan" is the Qinling Mountain, which is ~1500-m higher than the surface of "Dong Yuan", and to the north of it is the Guanzhong Basin, which is ~150-m lower than the surface of "Dong Yuan" (Fig. S1b). To the north of the Guanzhong Basin is the main body of the classic CLP (Fig. S1a). Previous studies have widely confirmed that loess around Weinan can be used to reconstruct past climate and environment changes at orbital- and millennial-scale during the Quaternary (e.g. Liu et al., 1994; Guo et al., 1996; Liu and Ding, 1998; Hao and Guo, 2005; Sun et al., 2010; Kang et al., 2013). However, there is still a lack of high-resolution Holocene records here.

The Weinan loess section in this study is about 600 km to the southeast of the landward limit of the modern EASM front (Fig. 1a). In addition, considering the decline of EASM intensity since the early or middle Holocene (Wang et al., 2005, 2008; Lu et al., 2013; Chen et al., 2015), it is reasonable to say that, the Weinan Holocene loess section can be influenced by the EASM throughout the Holocene. Modern mean annual precipitation and temperature are 645 mm and 13.6 °C respectively at Weinan, with rainfall mainly occurring in summer, brought by EASM winds. During winter and spring, the weather here is generally cold and dry, influenced by the EAWM.

3. Material and methods

3.1. Site description and sampling

The Weinan loess outcrop (Fig. 1b and Fig. S2a) was made in a brickyard years ago. The boundary between the uppermost palaeosol (S0) and beneath typical loess (L1) is clear from field observation. Based on the soil texture, soil color etc. (Fig. 1b and c and Fig. S2a), the Weinan loess outcrop can be divided into three parts, including typical loess (L1) at a depth below 2.7 m, a strongly-developed palaeosol (S0) at a depth of ~2.7–1.2 m, and a relatively weakly-developed palaeosol (L0) at a depth above ~ 1.2 m. Specifically for loess from a depth of 1.9–0.0 m, focused upon in this study, the soil becomes gradually loose and changes from brownish to yellowish. In addition, there is a relatively strongly-developed palaeosol unit at a depth of 0.8–0.6 m.

Fig. 1b shows the weathered outcrop. To obtain fresh samples, a new 3.5-m pit was excavated at Weinan after removal of the uppermost ~20-cm severely-disturbed loess (Fig. 1c). Powder samples, used for MS and grain size analysis, were obtained at 2-cm