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Reconciliation of hydroclimate sequences from the Chinese Loess Plateau and low-latitude East Asian Summer Monsoon regions over the past 14,500 years

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ABSTRACT

We discuss replicated stalagmite $\delta^{18}O$ records with interannual-to-multidecadal resolution from Lianhua Cave on the Chinese Loess Plateau to illustrate the precipitation history of the East Asian Summer Monsoon (EASM) region over the last 14.5 thousand years (ka BP, before 1950 CE, hereafter), and to re-evaluate the inconsistency in the proxy-inferred palaeoclimate time series in northern China. Agreement between the stalagmite $\delta^{18}O$ from Lianhua and other caves from central-southern China indicates that regional climate changes after the Last Glacial were concurrent across mainland China, indicating that insolation was the primary factor controlling the evolution of the Asian Summer Monsoon (ASM). The stalagmite ^{18}O enrichment of 2.5‰ in the Younger Dryas and 1.7‰ during the 8.2-ka BP event in Lianhua were larger than those in caves from central and southern China. The evidence suggests that different meridional responses of weak precipitation conditions in the ASM realm occurred during these two abrupt events, driven by high-latitude forcing in the Northern Hemisphere. The heterogeneous hydroclimate sequences in northern China inferred from different natural archives are most likely attributable to the complexity of the formations and/or some chronological uncertainty.

1. Introduction

The East Asian Summer Monsoon (EASM) is an integral part of the Asian Summer Monsoon (ASM) system, providing the majority of rainfall to the most densely populated areas of China. The hydroclimate in the Chinese Loess Plateau (CLP), located in northern China, is associated with the EASM variability (*e.g.*, Xiao et al., 2002; Li et al., 2004; Chen et al., 2006; Zhao et al., 2013). An intensification in the southerly monsoonal airflow results in an extension of the rainfall belt into the arid interior of the continent and a complementary reduction in desert coverage in northern China (*e.g.*, Liu and Ding, 1998; Yang and Scuderi, 2010; Lu et al., 2013). This induced environmental change has dominated the regional ecological system (*e.g.*, Li et al., 2004; Zhao et al., 2009) and has also affected the rise of civil practices, such as agriculture (Li et al., 2009) and human society (*e.g.*, Zhang et al., 2008). Over recent decades, diverse natural archives, including loess (Xiao et al., 2002; Sun et al., 2010), aeolian deposits (Yang and Scuderi, 2010), lacustrine sediments (Shen et al., 2005), and speleothems (Dykoski et al., 2005; Sinha et al., 2005; Wang et al., 2005; Hu et al., 2008; Cai et al., 2010; Dong et al., 2010; Ma et al., 2012; Lone et al., 2014; Zhang et al., 2014; Cai et al., 2015) have been used to improve our understanding of the evolution of regional climates since the previous deglaciation period to aid water resource management and the establishment of a sustainability policy.

Based on radiocarbon and optically stimulated luminescence (OSL) dating, Wang et al. (2010) summarised previous lake and loess records to show that Holocene hydroclimatic changes in northern China were asynchronous with the southern EASM regions. Recent loess and dune proxy records from northern China suggest that the onset of wet climatic conditions after the Last Glacial period occurred several thousand years after the summer insolation peak at 10–11 ka BP (Xiao et al., 2002, 2004; Lu et al., 2005; Sun et al., 2006; Lu et al., 2013). However, their suggestions are challenged by the stalagmite records from southern and central China (Dykoski et al., 2005; Dong et al., 2010) and CLP lake records (Jin et al., 2004; Li et al., 2004; Jiang et al., 2006, 2009). These records suggest a direct monsoonal response to insolation forcing during the Early Holocene. Although millennial-scale changes in the EASM responded rapidly to changes in the North Atlantic climate during

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the 8.2 ka BP event and the Younger Dryas (YD) (*e.g.*, Chen et al., 2001; Ma et al., 2012; Y. Liu et al., 2013; D. Liu et al., 2013), their nature across the entire extent of monsoonal China is not well understood. For example, two stalagmite records from Dongge Cave in southern China (Wang et al., 2005; Cheng et al., 2009) show an obvious $\delta^{18}O$ anomaly occurring at 8.4–8.1 ka BP, which is also recorded in the Heshang Cave in central China (Y. Liu et al., 2013). Stalagmite $\delta^{18}O$ sequences from the Sanbao Cave in central China and the Nuanhe Cave in north-eastern China do not register this event (Dong et al., 2010; Wu et al., 2012). Hong et al. (2010) and Stebich et al. (2010) argued that a change in EASM precipitation during the YD remains an open question. Hong et al. (2005) used the Hani (42°13′N, 126°31′E) peat cellulose carbon stable isotope record to propose enhanced precipitation in northern China during the YD. However, this implication was not supported by high-resolution pollen records, which show a reversal of climatic conditions in Lake Sihailongwan (Stebich et al., 2009), located ~15 km northeast of the Hani site. Building more detailed palaeorecords for northern China, with improved timeframes, is critically important for clarifying the evolution of the regional hydroclimate.

In this study, we first built a new absolute-dated multidecadal-resolved oxygen isotope time series using three stalagmites collected from Lianhua Cave for the CLP. The composite Lianhua $\delta^{18}O$ record was compared with previous well-dated stalagmite sequences to show the synchronicity of regional precipitation variations since the Last Glaciation over the entire monsoonal region. We showed the variable meridional impact of the high-latitude forcing originating in the North Atlantic on the regional hydrology during the YD and the 8.2-ka BP event. Finally, we propose possible causes for the lack of concurrence in the proxy-inferred CLP hydroclimate sequences.

2. Cave site and samples

Lianhua Cave (38°10′N, 113°43′E), at an elevation of 1200 m, is located on the CLP, Shanxi Province, northern China (Fig. 1). The temperature (1985–2004 CE) varies from −2.5 °C in winter to 28 °C in summer (Fig. 2), recorded at the nearest meteorological station, Shijiazhuang (elevation 80 m), located 80 km east of the cave (Fig. 1). The mean annual precipitation is 530 mm (Fig. 2). This site is in an arid–semiarid zone in the northern margins of the EASM region (Yamanaka et al., 2004), with distinctive wet summers and dry winters. More than 81% (1985–2004 CE) of annual precipitation falls in summer, from May to September. The inflow of warm/humid air delivered by the EASM extends north-westerly into the interior as far as the China–Mongolia border. In winter, the southward-migrating Siberian High cold, dry air mass dominates the regional climate.

Lianhua Cave, with a small entrance 0.5 m in width and 0.5 m in height, is 200 m in length and overlain by ~50 m of Ordovician limestone of the Ma-Jia-Gou Group (Qian, 1960). The temperature in the cave is 11 °C. The humidity in the innermost tunnel is 95% on average, where three calcite stalagmites located 20–30 m apart (LH4, LH5, and LH9) were collected. Stalagmites were halved and polished for ^{230}Th dating and oxygen/carbon stable isotope analysis (Fig. 3).

3. Methods

Twenty-seven subsamples from the three collected stalagmites (15 subsamples from LH4, eight subsamples from LH5, and four subsamples from LH9, 100–200 mg each) were drilled for U–Th chemistry (Shen et al., 2003) and ^{230}Th dating (Shen et al., 2002, 2012) (Fig. 3). Uranium–thorium isotopic measurements were performed using a multi-collection inductively coupled plasma mass spectrometer (MC-ICP-MS,) Thermo Finnigan Neptune, in the High-Precision Mass Spectrometry and Environment Change Laboratory (HISPEC), Department of Geosciences, National Taiwan University (Shen et al., 2012). A gravimetrically calibrated (Cheng et al., 2013) triple-spike, ^{229}Th–^{233}U–^{236}U, isotope dilution method was employed to correct any mass bias and to determine the U–Th content and isotopic composition (Shen et al., 2012). All date errors are given to two standard deviations, unless otherwise noted.

Based on the obvious changes in lithology of the polished sections of stalagmites LH4, LH5, and LH9 (Fig. 3), six subsamples were obtained along the central growth axis of each stalagmite, and these were analysed using x-ray diffraction (XRD) on a powder diffractometer, Rigaku D/Max-2500VL/PC, located at the Institute of Testing Service Center, Nanjing Normal University, China. The XRD measurements indicate that the three stalagmites are all composed of calcite, and the mineralogical composition is homogeneous throughout the growth period (Fig. 4a).

For stable isotopic measurements, 829 subsamples, 10–20 μg each, were drilled using a 0.3 mm diameter carbide dental burr at 1 mm intervals, except for 0.5 mm intervals at depths from 139 to 155 mm in stalagmite LH4. The corresponding temporal resolution was 4–47 years. Five coeval subsamples from five horizons were selected arbitrarily from LH4 and LH5 and subjected to the "Hendy Test" (Hendy, 1971) to evaluate the oxygen isotopic equilibrium conditions during calcite

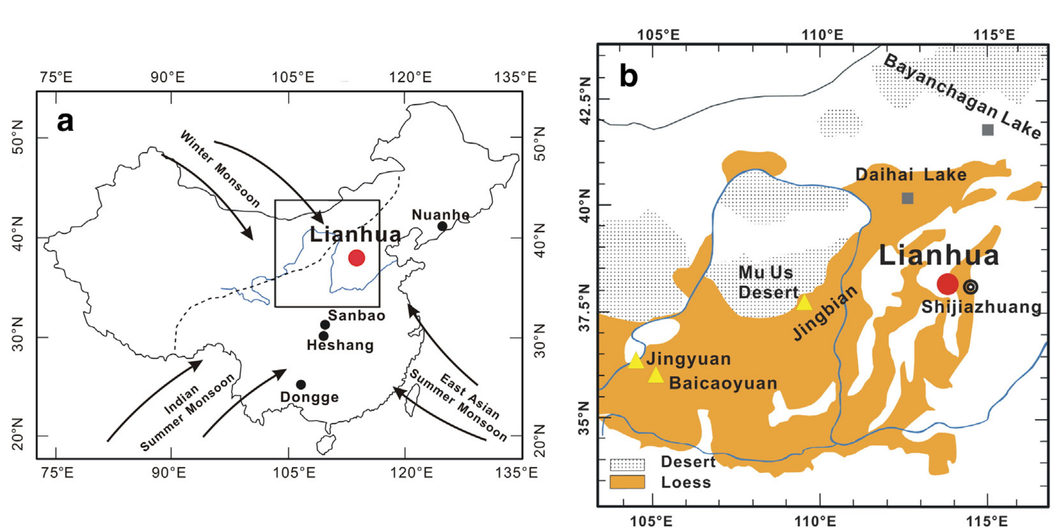

Fig. 1. **(a)** Location of Nuanhe (Wu et al., 2012), Lianhua (this study, red circle), Sanbao (Dong et al., 2010), Heshang (Hu et al., 2008), and Dongge (Wang et al., 2005) caves. The arrows show the modern monsoonal system in China, including the East Asian and Indian summer and winter monsoons. The dashed line denotes the averaged present-day limit of the summer monsoon. **(b)** An enlarged regional CLP map (32.9–43.7°N, 103.4–117.0°E) with desert (dotted areas), loess (triangles), and lake (squares) sites.