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East Asian Summer Monsoon variations in the past 12.5 ka: High-resolution $\delta^{18}O$ record from a precisely dated aragonite stalagmite in central China

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ABSTRACT

Due to possible aragonite to calcite transformation resulting in alteration in isotopic signatures and a bias in age-dating, aragonite speleothems are often excluded from paleoclimatic archives. However, aragonite stalagmites contain ppm-level uranium content, making them much easier to date, achieving higher age-dating precisions than calcite stalagmites. In this regard, provided aragonite-to-calcite transformation did not occur, aragonite stalagmites are potentially well suited for Holocene climate research, given their climate proxies can be placed into a better constrained chronological framework. In this paper, we present high-precision U/Th dates and O isotopic time series for a 82 cm long, continuous growth aragonite stalagmite, LH2, from Lianhua Cave, Hunan Province, China, and discuss East Asian Summer Monsoon (EASM) variability for the last 12.5 ka BP (before present). The U/Th-dated $\delta^{18}O$ sequence with a mean 16-year resolution and the growth rate pattern of LH2 show that EASM experienced a strengthening stage, a strong stage and a weakening stage during the last 12.5 ka. During the YD (12.5–11.5 ka BP), heavy $\delta^{18}O$ values and low growth rate indicate a weak monsoon period. During the Preboreal (from ~11.5 to 10.6 ka BP), $\delta^{18}O$ values decreased dramatically (~1.94‰) reflecting abrupt strengthening of the monsoon. From 10.6 to 4.2 ka BP, the record is characterized by the lightest $\delta^{18}O$ values and high growth rates, suggesting a strong monsoon period. The summer monsoon weakened substantially after 4.2 ka BP, as inferred from gradually increasing $\delta^{18}O$ values and decreasing growth rate. Overall, the intensity of the EASM is regulated by summer insolation at 30°N during the last 12.5 ka. Although oxygen isotope fractionation is different between aragonite–H_2O and calcite–H_2O because of Rayleigh Fractionation Law, the overall temporal pattern of $\delta^{18}O$ values from aragonite stalagmite LH2 is concordant with other high-resolution Holocene calcite stalagmite records from South China. The comparison among these records shows that the Holocene Optimum was synchronous across Asian continental region influenced by the EASM and Indian Summer Monsoon (ISM), lasting from ~10.6 to 4.2 ka BP, as reflected by consistently lighter $\delta^{18}O$ values among all these records regardless of their latitudinal difference. These records do not support previously reported asynchronism between EASM and ISM. In details, the long-term $\delta^{18}O$ trend in LH2 is punctuated by a number of centennial fluctuations. For instance, two weak monsoon events occurred at 9232 ± 57 yr BP and 8137 ± 21 yr BP, correlating in time with cooling events in Greenland ice cores. The latest weak monsoon event centered at 302 ± 8 yr BP which is related to the Little Ice Age (LIA). In addition, the monsoon intensity derived from our record also shows a strong connection with latitudinal migration of the Inter-Tropical Convergence Zone (ITCZ) as recorded in the Cariaco Basin sediments. Spectral analysis of $\delta^{18}O$ values shows that significant peaks match with solar periodicities of 208 yr (de Vries cycle), 86 yr (Gleissberg cycle) or related to $\Delta^{14}C$ production suggesting shorter-term monsoon variations are forced by solar radiation. Overall, our study suggests that the $\delta^{18}O$ record in the aragonite stalagmite is highly consistent with those derived from calcite stalagmites,

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suggesting that aragonite stalagmites are suitable for palaeoclimate reconstruction, especially for the Holocene period, as aragonite–calcite transformation has not occurred.

1. Introduction

The East Asian Summer Monsoon (EASM) has always played a critical role in the sustainability of agricultural practice and human life in the densely populated East Asia. Thus reconstructing the EASM variability during the Holocene and unraveling the mechanisms that drive EASM variations have been important issues over last decades. Owing to its high-resolution, multi-proxy records and absolute chronological control, stalagmites prove to be an excellent archive of Holocene–Pleistocene climate and environmental processes (McDermott, 2004; Fairchild et al., 2006; Henderson, 2006). Stalagmite $\delta^{18}O$-based high-resolution climate reconstructions have made significant contributions to our understanding of EASM (Ku and Li, 1998; Li et al., 1998; Wang et al., 2001, 2005, 2008; Paulsen et al., 2003; Yuan et al., 2004; Dykoski et al., 2005; Cosford et al., 2008, 2009; Zhang et al., 2008; Li et al., 2011a,b), as highlighted below:

(1) *The stalagmite $\delta^{18}O$ evidence of orbital forcing on EASM.* When solar insolation increases in the Northern Hemisphere, ITCZ (Intertropical Convergence Zone) migrates northward and EASM strengthens, which brings more rainfall over eastern China and results in a lighter $\delta^{18}O$ value in stalagmites (Yuan et al., 2004; Dykoski et al., 2005; Wang et al., 2005, 2008; Duan et al., 2009; Dong et al., 2010).

(2) *Demonstration of a close correlation between EASM variability and the temperature change in Greenland on millennial to centennial time-scales* (Wang et al., 2001, 2005, 2008; Yuan et al., 2004; Dykoski et al., 2005; Shao et al., 2006).

(3) *Revealing a teleconnection between EASM and the North Atlantic, i.e., the North Atlantic cooling events matching with episodes of weak EASM* (Dykoski et al., 2005; Wang et al., 2005; Liu et al., 2013). Although the above progress has greatly increased our knowledge on EASM, many questions still remain unanswered, e.g.: (1) Is the Holocene Optimum time-transgressive? (2) Do EASM and ISM change in phase? (3) What causes the centennial–decadal scale variations of EASM? (4) Is there any cyclicity of weak monsoon events? In addition, the repeatability of climate records in stalagmites still need further investigation, for example, stalagmite SB10, from Shenglongjia, central China, recorded an abrupt oxygen isotopic variation at 4.3 ka BP (Shao et al., 2006), but other stalagmites in the same cave failed to record it (Duan et al., 2009; Dong et al., 2010). Similarly, in Dongge Cave (central China), the sharp shift in $\delta^{18}O$ of stalagmite D4 occurring at ~3.5 ka BP (Dykoski et al., 2005) was not observed in stalagmite DA from the same cave (Wang et al., 2005).

The application of aragonite stalagmites as palaeoclimatic records has also been somewhat problematic. It has been well demonstrated that calcite stalagmites record variations in the intensity of Asian monsoon accurately (Wang et al., 2001, 2005, 2008; Yuan et al., 2004; Cheng et al., 2005; Dykoski et al., 2005; Cosford et al., 2008; Hu et al., 2008; Zhang et al., 2008; Yang et al., 2010) since the information about precipitation and air-mass transport is captured by the oxygen isotope ratios ($\delta^{18}O$) of stalagmite calcite (Rozanski et al., 1992). There is, however, uncertainty in aragonite stalagmite measurements due to the instability of its mineral phase. Aragonite can spontaneously transform into calcite in caves (Frisia et al., 2002), which results in the loss of the uranium and the reversal of the uranium-series ages (Ortega et al., 2005; Lachniet et al., 2012). The initial stable isotopes of precipitation are also believed to have changed after phase transition (Fairchild et al., 2006). On the other hand, it is also possible for a stalagmite to precipitate aragonite continuously without phase transition. In this regard, its $\delta^{18}O$ may reliably record climate changes and replicate the records of the coeval calcite stalagmites, as exemplified by the $\delta^{18}O$ record of an aragonite stalagmite from Furong Cave, China, which has been successfully used as a historic dryness/wetness index (Li et al., 2011a). Compared with calcite stalagmites, aragonite stalagmites also have some advantages in Holocene climatic reconstruction, such as the ppm-level uranium content allowing for easier and more precise U-series dating. Therefore, pure aragonite stalagmites may provide good archives for past high-resolution climate reconstruction. Here we present isotopic records of an aragonite stalagmite LH2 recovered from Lianhua Cave, central China, and discuss the EASM related climatic information over the last 12.5 ka.

2. Location, environment and sample description

Lianhua Cave (109°32′E, 29°29′N, elevation ~455 m, Fig. 1) is located at ~30 km from the town of Luota in northwestern Longshan County, Hunan province, China. The area is situated in the transitional slope zone between the Yunnan–Guizhou Plateau (~1000 m a.s.l) and the Hunan Basin (~100 m a.s.l), and is characterized by multi-level karstic plateaus. The bedrock outcrops in this region are mostly Paleozoic carbonate.

Lianhua cave is about 570 m long, 10–24 m high and 11–36 m wide. Its orientation and formation were controlled by the local fractures and fault system. Abundant drip water in the cave

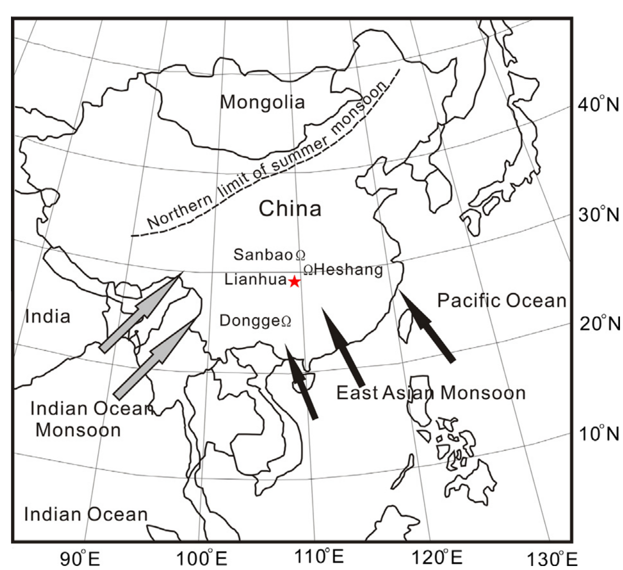

Fig. 1. Location map of Lianhua cave. The red pentacle denotes Lianhua Cave and Sanbao (Dong et al., 2010), Heshang (Hu et al., 2008) whilst the Ω signifies Dongge caves (Dykoski et al., 2005). Arrows indicate generalized modern summer monsoonal winds. Dashed line represents the northern limit of the summer monsoon. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)