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Multi-scale Holocene Asian monsoon variability deduced from a twin-stalagmite record in southwestern China

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ABSTRACT

We present two isotopic ($\delta^{18}O$ and $\delta^{13}C$) sequences of a twin-stalagmite from Zhuliuping Cave, southwestern China, with ^{230}Th dates from 14.6 to 4.6 ka. The stalagmite $\delta^{18}O$ record characterizes orbital- to decadal-scale variability of Asian summer monsoon (ASM) intensity, with the Holocene optimum period (HOP) between 9.8 and 6.8 ka BP which is reinforced by its co-varying $\delta^{13}C$ data. The large multi-decadal scale amplitude of the cave $\delta^{18}O$ indicates its high sensitivity to climate change. Four centennial-scale weak ASM events during the early Holocene are centered at 11.2, 10.8, 9.1 and 8.2 ka. They can be correlated to cold periods in the northern high latitudes, possibly resulting from rapid dynamics of atmospheric circulation associated with North Atlantic cooling. The 8.2 ka event has an amplitude more than two-thirds that of the Younger Dryas (YD), and is significantly stronger than other cave records in the Asia monsoon region, likely indicating a more severe dry climate condition at the cave site. At the end of the YD event, the $\delta^{13}C$ record lags the $\delta^{18}O$ record by 300–500 yr, suggesting a multi-centennial slow response of vegetation and soil processes to monsoon enhancement.

Introduction

The warm Holocene, after the termination of the cold Younger Dryas (YD) event, is an important period for accelerated development of human civilizations. Understanding the paleohydroclimatic dynamics is, therefore, of importance for sustainable management and adaptation on Earth, especially in the monsoonal realms with dense populations. Two characteristic occurrences are the millennial Holocene optimum period (HOP) and abrupt centennial cooling events.

Investigating the spatio-temporal patterns of climate history in a given region may reveal underlying climate-forcing mechanisms. An et al. (2000) summarized the diachronism of the HOP within China, as defined by peak East Asian summer monsoon (EASM) precipitation, through multi-proxies including lake levels, pollen profiles, and loess/paleosol records. In general, the timing of the maximum Holocene EASM precipitation became gradually later from northwestern to southeastern China, which was interpreted as a response to changing seasonality associated with orbital forcing of the climate, coupled with the progressive decrease in summer insolation through the Holocene. He et al. (2004) also explained a similar phenomenon from west to east China, and proposed that altitudinal differences were a factor leading to different durations of the HOP. In contrast, later research (e.g., Cai et al., 2010; Jiang et al., 2012) argued that changing sea surface temperature (SST) in the western tropical Pacific was likely an important forcing for the summer monsoon precipitation changes in central and northern China, which resulted in spatio-temporal distributions that were distinct from those proposed by An et al.

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(2000). Additionally, Zhou et al. (2007) suggested that the Holocene maximum occurred between 10 and 5 ka BP in both southern and northern China, consistent with a global pattern and not a local expression. Because stalagmite $\delta^{18}O$ generally reflects the broad regional scale of monsoonal circulation associated with summer precipitation, it is limited in exactly expressing the characteristics of the HOP in local areas. In addition, the demarcation of the termination of the HOP is somewhat subjective (e.g., 6.5 ka BP at Sanbao Cave from Dong et al. (2010), versus at 4.7 ka BP by Cai et al. (2010)). Under the circumstances, we need to find an indicator that tracks local ecosystem and environment variations more directly, such as calcite $\delta^{13}C$, which may reflect the local conditions of the cave, and in turn has potential to respond to paleoclimate changes (Zhang et al., 2004; Zhu et al., 2006; Cosford et al., 2009; Liu et al., 2012; Wu et al., 2012), although the impact of various processes on calcite $\delta^{13}C$ is complex (McDermott, 2004; Mickler et al., 2006).

Also important are the short cooling events that occurred in the early Holocene and their associated forcing mechanisms. The most prominent oscillations since the relatively stable Holocene began, the so-called Preboreal Oscillation (PBO), 9.2 ka, and 8.2 ka events have been recorded in Greenland ice cores (e.g., Rasmussen et al., 2007), where $\delta^{18}O$ and accumulation anomalies are present. The 10.2 and 10.9 ka events are also exhibited in most of the individual cores. Bond et al. (2001) found that centennial to millennial time scale changes peaked at 11.3 ka, 10.3 ka, 9.4 ka and 8.2 ka in debris proxies from Atlantic sediment cores, all of which likely correlated with those recorded in Greenland. Given the different routings of the Lake Agassiz overflow and outbursts to the oceans (Teller et al., 2002, 2004), evidence for the PBO has been found in various indicators, such as microfossils, macroremains and pollen in Europe (Bos et al., 2007) and the Nordic Seas (Hald and Hagen, 1998), as well as across the North Atlantic (Alley et al., 1997, 2005; Bond et al., 2001). In the Asian monsoon (AM) domain, a large body of stalagmite records have reported correlations with monsoon events (Dykoski et al., 2005; Wang et al., 2005; Cai et al., 2008; Fleitmann et al., 2008; Cheng et al., 2009), probably due to rapid responses to Atlantic climate via coupled atmospheric and ocean processes (Dong and Sutton, 2002; Zhang and Delworth, 2005), or through rapid atmospheric transmission alone (Liu et al., 2013). However, due to the uncertainties in dating and the different temporal resolutions of various indices including the calcite-$\delta^{18}O$ records, the timing of most of the cooling fluctuations is not precisely correlated. In addition, the sensitivity (or amplitude) of the stalagmite $\delta^{18}O$ ($\leq$1‰) in the AM region is generally lower than that of ice records (1–2‰) and records in South America (~2.5‰) reported by Cheng et al. (2009), and it is difficult to obtain more detailed information for these events. It is thus necessary to find more sensitive stalagmite records with better karst conditions and weaker reservoir effects.

A high-resolution, ^{230}Th-dated isotopic record generated from a twin-stalagmite (based on its morphological features, see Fig. 2) from Zhuliuping (ZLP) Cave, southwestern China, has been used to reconstruct the history of monsoonal precipitation in the study region since the last deglaciation. The objectives of this study are (i) to characterize the climatic changes since the last deglaciation, compared to other monsoon proxies in the broad monsoonal regions; (ii) to confirm the onset and end of the HOP using $\delta^{18}O$ covarying with $\delta^{13}C$, and to thus gain a better understanding of the Holocene diachronism; and (iii) to discuss several salient short term coolings that occurred in the early Holocene through systematic comparisons between the site and the Greenland $\delta^{18}O$ records, to verify the degree of correlation between monsoon weakening and North Atlantic cooling.

Material and methods

Location and sample description

Zhuliuping Cave (26°01′N, 104°57′E, elevation ~1217 m) is located on the Yun-Gui Plateau, southwestern China, about 350 km northeast of Dongge Cave (Yuan et al., 2004; Wang et al., 2005) and 310 km northwest from Yamen Cave (Yang et al., 2010) (Fig. 1). The mean annual rainfall and temperature at this site are approximately 1400 mm and 14°C, respectively. In winter, the Siberian cold air mass is obstructed by the Ta-pa Mountains, the Qinling Mountains and the Tibet Plateau; and the regional temperature is 3°C higher than those at the same latitudes, with a local minimum precipitation of 26.7 mm in December averaged over 47 yr (1961–2007 AD, from a local meteorological station). In summer, it is influenced by the Indian summer monsoon (ISM) and the EASM, and seasonal precipitation increases distinctly, with a mean maximum rainfall of 264.9 mm in July.

The cave site experiences severe rocky degradation, and the flora above is mostly composed of weeds and bushes. But the natural vegetation in this area is more complicated, which is characterized by a vertical distribution, including the Alpine shrub meadow, broadleaved deciduous/evergreen forest and coniferous forest. It is overlain by approximately 30–40 m of Triassic limestone bedrock with a thin soil cover. The entrance of ZLP Cave is towards the west, located on the upper part of the mountain. A narrow passage, approximately 20 m long, leads from the entrance to the poorly ventilated main chamber. The measured relative humidity is 100% and temperature is close to the regional annual mean at the sampling site in the cave. Stalagmite ZLP (Fig. 2), collected from a platform in the main chamber, is composed of two distinct formations. A first columnar-like stalagmite, named ZLP2, grew 640 mm long with a diameter ranging from 30 to 70 mm. A second slimmer branch (ZLP1, 936 mm in length), with a 40–50 mm-diameter, was deposited on one side of ZLP2. The two sections are separated by a 2 mm-thick dark-compact layer, suggesting different drip sites.

The polished surface of the stalagmite is comprised of different calcite fabrics (Fig. 2). The first one is made of continuous layer couplets composed of transparent-compact and white-porous calcite deposit, from the top to 200 mm on ZLP2 and from 470 to 510 mm on ZLP1 (Supplementary Fig. 3a), similar to that defined by Genty and Quinif (1996). This may indicate a cave environment with fast growing specimens, in response to seasonal changes in cave microclimate and hydrology (e.g., Mattey et al., 2008). A second fabric of thin discrete layers is observed at 380–470 mm and 510–936 mm on ZLP1 (Supplementary Fig. 3b), interrupted irregularly by transparent-compact and pure calcite sections. The basal part of ZLP2 (200–640 mm) is characterized by lithologic homogeneity and unclear banding couplets (Supplementary Fig. 3c). Especially below the 530 mm portion, visible layers are less clear and even disappear, suggesting a lower growth rate for this interval. The last fabric, from the top to 380 mm on ZLP1, appears to be separated periodically by dark and yellow clay-bands, each about 1–2 mm thick and containing some voids and thinner layers (Supplementary Fig. 3d), which either arise from intermittent precipitation (Genty and Quinif, 1996), or from changes in coverage conditions above the cave (Frisia et al., 2000).

Analytic methods

Nineteen subsamples, 100–200 mg each, were collected along the growth axis with a 0.9-mm-diameter carbide dental drill for ^{230}Th dating. Sample preparation procedures are similar to those described in Kelly et al. (2006). Uranium and thorium contents and