



Early-Holocene monsoon instability and climatic optimum recorded by Chinese stalagmites

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Xunlin Yang,¹ Hong Yang,^{1,2} Baoyan Wang,¹ Li-Jung Huang,^{3,4}
Chuan-Chou Shen,^{3,4} R Lawrence Edwards⁵ and Hai Cheng^{5,6}

Abstract

The timing and duration of the Holocene East Asian summer monsoon (EASM) maximum and the interpretation of Chinese stalagmite $\delta^{18}\text{O}$ records have long been disputed. Notably, interpretations of Holocene EASM variations are frequently based on a single record or study area and are often contradictory. In this study, we conducted stable isotope analyses of four Holocene stalagmites from Chongqing, southwest China. The results reveal differences in the timing of the Holocene EASM maximum and to try to resolve the inconsistency we analyzed and statistically integrated a total of 16 Holocene stalagmite records from 14 caves in the EASM region. The resulting synthesized Holocene stalagmite $\delta^{18}\text{O}$ ($\delta^{18}\text{O}_{\text{syn}}$) record is in agreement with other EASM records and confirms that stalagmite $\delta^{18}\text{O}$ records are a valid indicator of EASM intensity, rather of local precipitation amount. The $\delta^{18}\text{O}_{\text{syn}}$ record shows that the EASM intensified rapidly from the onset of the early Holocene; notably, however, there were distinct EASM oscillations in the early Holocene, consisting of three abrupt millennial-scale events. This indicates that, contrary to several previous interpretations, the early Holocene EASM was unstable. Subsequently, during 8–6 kyr BP, the EASM was relatively stable and strong, with the strongest monsoon occurring during 8–7 kyr BP. This evidence of a stable and strong mid-Holocene EASM in eastern China is in accord with the classical view of a mid-Holocene Optimum in China.

Keywords

climatic optimum, early Holocene, East Asia, millennial-scale events, Stalagmite $\delta^{18}\text{O}$, summer monsoon

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Introduction

The East Asian summer monsoon (EASM) is an important component of atmospheric circulation and plays a major role in global hydrological and energy cycles (An et al., 2000; Wang et al., 2005). It significantly affects the climate, environment and socioeconomic development of East Asia and other regions (Yang et al., 2013). However, the evolution of the EASM during the Holocene, especially the timing of the Holocene Optimum/EASM precipitation maximum, remains controversial (An et al., 2000; Chen et al., 2015, 2016a; Goldsmith et al., 2017; Lu et al., 2013; Shi et al., 1994; Wang et al., 2005). Shi et al. (1994) summarized pollen, lake level, and paleosol records from the EASM region and proposed that the climate of China during 7.2–6.0 kyr BP was warm, wet, and stable—that is, the Holocene Megathermal Maximum. A recent quantitative precipitation reconstruction from Gonghai Lake, in North China, showed that the EASM maximum occurred during the middle Holocene (7.8–5.3 kyr BP) (Chen et al., 2015), supporting the concept of a mid-Holocene Optimum in China. However, a sequence of eutrophic peat/mud sediments from Dahu Lake, in southern China, revealed a warm and humid interval during 10.0–6.0 kyr BP which supported the interpretation of an early-Holocene maximum (Zhou et al., 2004). In addition, a lake-level reconstruction from Lake Dali (Goldsmith et al., 2017), at the edge of the monsoon region in North China, indicated the occurrence of very high lake levels in the early and middle Holocene, and in addition there was a significant negative correlation between lake level and the stalagmite $\delta^{18}\text{O}$ record

for China, which indicates that stalagmite $\delta^{18}\text{O}$ records in China reflect changes in summer monsoon intensity/monsoon precipitation. However, Chen et al. (2016b) and Yang et al. (2014) suggested that the stalagmite record supported an early-Holocene Optimum/EASM maximum – in contrast to traditional EASM or EASM precipitation records from northern China (Lu et al., 2013; Xiao et al., 2008) – and they questioned the reliability of stalagmite records as a proxy for changes in EASM intensity/precipitation (Chen et al.,

¹Chongqing Key Laboratory of Karst Environment, School of Geographical Sciences, Southwest University, China

²Department of Geography and Environmental Science, University of Reading, UK

³High-Precision Mass Spectrometry and Environment Change Laboratory (HISPEC), Department of Geosciences, National Taiwan University, Taiwan, ROC

⁴Research Center for Future Earth, National Taiwan University, Taiwan, ROC

⁵Department of Earth Sciences, University of Minnesota, USA

⁶Institute of Global Environmental Change, Xi'an Jiaotong University, China

Corresponding author:

Xunlin Yang, Chongqing Key Laboratory of Karst Environment, School of Geographical Sciences, Southwest University, Chongqing 400715, China.

Email: xlyang@swu.edu.cn

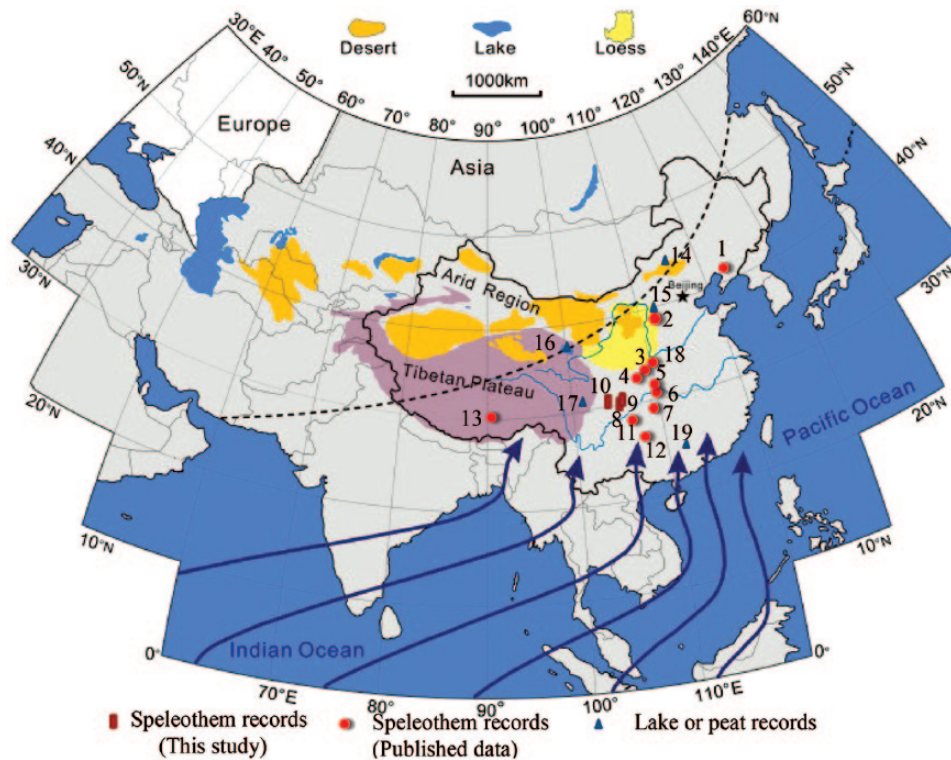


Figure 1. Sites with Holocene stalagmite records from the Asian summer monsoon region and locations of moisture or precipitation records from northern China mentioned in the text. The modern Asian summer monsoon limit is shown by the green dashed line.

1. Nuanhe Cave (Wu et al., 2011); 2. Lianhua Cave (Dong et al., 2015); 3. Buddha Cave (Li et al., 2000); 4. Jiuxian Cave (Cai et al., 2010); 5. Sanbao Cave (Dong et al., 2010); 6. Heshang Cave (Hu et al., 2008); 7. Lianhua Cave (Zhang et al., 2013); 8. Jinfo Cave (this study); 9. Heifeng Cave (this study); 10. Shizi Cave (this study); 11. Shigao Cave (Jiang et al., 2012); 12. Dongge Cave (Dykoski et al., 2005; Wang et al., 2005); 13. Tianmen Cave (Cai et al., 2012); 14. Dali Lake (Goldsmith et al., 2017); 15. Gonghai Lake (Chen et al., 2015); 16. Qinghai Lake (An et al., 2012); 17. Hongyuan peat bog (Hong et al., 2003); 18. Dongshiya Cave (Zhang et al., 2018); 19. Dahu Lake (Zhou et al., 2004).

2016b; Dayem et al., 2010; Pausata et al., 2011; Maher, 2008; Tan, 2009). Based on the assumption that stalagmite $\delta^{18}\text{O}$ records directly reflect EASM intensity, several researchers have reconstructed the EASM evolution on various timescales and proposed causal mechanisms (e.g. Cheng et al., 2012, 2016; Wang et al., 2005, 2008). More recently, however, it was proposed that stalagmite records in China are indicators of water vapor source rather than EASM intensity (Chen et al., 2016b; Pausata et al., 2011; Maher, 2008; Tan, 2009).

The forgoing summary highlights that the controversy regarding the pattern of Holocene climate change in China focuses on the early to middle Holocene, and that the contrasting interpretations of the stalagmite $\delta^{18}\text{O}$ record in China are so far unresolved. Given the possibility of regional differences in the processes of carbonate deposition, it is important to analyze stalagmite $\delta^{18}\text{O}$ records from multiple sites. Accordingly, in this study, four Holocene stalagmite records from three caves (Jinfo, Heifeng, and Shizi) in Chongqing, southwest China, were collected and analyzed. We then combined the results from these caves with an additional 12 stalagmite records from the EASM region of China and use them to discuss the pattern of early- to mid-Holocene climate change in eastern China. In addition, by comparing the stalagmite records with other proxy records, we further assess the climatic significance of stalagmite $\delta^{18}\text{O}$ records in East Asia.

Materials and methods

Four Holocene stalagmites were collected from three caves in Chongqing (Figure 1), in the upper reaches of the Yangtze River, in southwest China. The region has a typical EASM climate, with an average annual precipitation of 1125 mm, which occurs mainly from May to September; summer precipitation comprises up to about 70% of the total annual precipitation. Stalagmite QM09, with a length of 480 mm, is from Shizi Cave ($29^{\circ}40'56''\text{N}$,

$106^{\circ}17'17''\text{E}$, altitude 401 m) located in Qingmuguan Town, northwest of Chongqing City. The Qingmuguan karst system consists of carbonate of the lower Triassic Jialingjiang Formation with a thickness exceeding 600 m. Exposed at the anticlinal axis, it is the oldest stratum at the site and is the main body of the mountain. Lithologically, the formation is mainly composed of gray-colored thick massive limestone, dolomite limestone and breccious limestone. Shizi Cave is a small underground river cave system. Stalagmite QM09 was collected from the rock wall 50 m from the entrance of the cave; a total of 24 ^{230}Th dates and 315 stable isotope measurements were obtained, with an average resolution of 30 years. Stalagmites J12 (length 395 mm) and J13 (length 210 mm) were collected from Jinfo Cave ($29^{\circ}01'00''\text{N}$, $107^{\circ}10'45''\text{E}$, altitude 2114 m), in southeast Chongqing, specifically in Mt. Jinfo of Nanchuan. The study site is located on the southeastern margin of Sichuan Basin, along the northern margin of the Yun-Gui Plateau and at the northern end of the Dalou Mountains. The uppermost rock unit comprising Mt. Jinfo is Permian limestone, and a huge and complex underground cave system has developed within this unit. The cave exhibits a corridor planar form and is 2800 m long, 8–25 m wide, and generally 8–12 m high. Stalagmites J13 and J12 were collected at locations 100 and 1200 m from the entrance of the cave, respectively. Twenty-eight ^{230}Th ages and 432 stable isotope measurements were obtained from stalagmite J13, with an average resolution of 27 years. In this study, only Holocene data are considered, and the length of the Holocene interval of stalagmite J12 is about 70 mm. Eight ^{230}Th dates and 161 stable isotope measurements were obtained from stalagmite J12, with an average resolution of 50 years. Stalagmite HF01 (length 130 mm) was collected 10 m from the entrance of Heifeng Cave (altitude 2132 m). Heifeng Cave is 1200 m from Jinfo Cave and its geological background is similar to that of Jinfo Cave. Heifeng Cave has a dendritic shape,

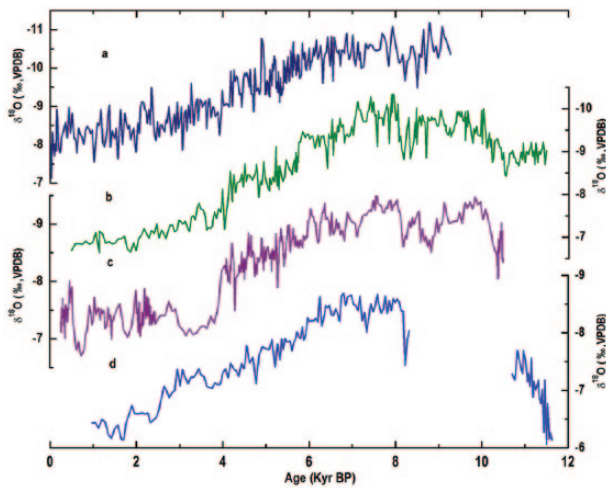


Figure 2. Holocene stalagmite $\delta^{18}\text{O}$ records from (a) Shizi Cave (stalagmite QM09), (b) Heifeng Cave (stalagmite HF01), (c) Jinfo Cave (stalagmite J13), and (d) Jinfo Cave (stalagmite J12), from Chongqing, southwest China.

consisting of the main channel of the underground river and two large caverns that expand along the northeastward fracture. Thirty ^{230}Th ages and 325 stable isotope measurements were obtained from Stalagmite HF01, with an average resolution of 30 years. The stalagmites from Jinfo Mountain are dense and contain high uranium concentrations. There is no evidence of recrystallization, erosion or hiatuses and hence they are highly suited to precise ^{230}Th dating. The stalagmites collected from Shizi Cave, in the Qingmu Guan Mountains, typically have low uranium concentrations which are likely to result in a larger dating error. Oxygen isotope measurements were made with a Finnigan Delta V Plus in Southwest University, China, and are reported as $\delta^{18}\text{O}$ (‰) with respect to the Vienna Pee Dee Belemnite standard (V-PDB). An international standard, NBS-19, was used to confirm that the 1σ measurement uncertainty was better than $\pm 0.1\%$. Measurements of ^{230}Th for stalagmites J12, J13, and HF01 were made with a Thermo-Finnigan Neptune multi-collector inductively coupled plasma mass spectrometer (MC-ICP-MS) in the Institute of Global Environmental Change, Xi'an Jiaotong University, and measurements of ^{230}Th for stalagmite QM09 were made in the High-Precision Mass Spectrometry and Environmental Change Laboratory, Department of Geosciences, National Taiwan University, using integrated MC-ICP-MS analysis. The analytical uncertainty of the dating was equal to or less than 1% (2σ). The age model for three stalagmites without hiatuses (QM09, J13, and HF01) was established by polynomial fitting, and the age model for stalagmite J12 (which has a hiatus) was done by linear interpolation. The methods used for ^{230}Th dating are described in Cheng et al. (2013) and Shen et al. (2012).

We also collected 12 published stalagmite Holocene records from the EASM region (Figure 1). These records have a high-precision U-Th chronology covering most of the Holocene. To facilitate data analysis and integration, the original stalagmite records were interpolated to a common time step using Analy-Series 2.0.4 (Paillard et al., 1996). The resolution of the new time series was 50 years and the $\delta^{18}\text{O}$ data was normalized using Equation (1):

$$x = \frac{x_i - x_{\min}}{x_{\max} - x_{\min}} \quad (1)$$

Here, x is the normalized value, x_i are interpolated isotope values, and x_{\min} and x_{\max} are the minimum and maximum values of the individual interpolated data series. The normalized data fall within the range of [0, 1]. To facilitate comparison of records, the values were adjusted using the following equation:

$$\delta^{18}\text{O}_i = x - 1 \quad (2)$$

Thus, the $\delta^{18}\text{O}_i$ values were within the range of [0, -1], in accordance with the original data series. To minimize the impact of regional differences, differences in the process of signal acquisition, and analytical errors, the $\delta^{18}\text{O}_i$ records were used to produce a stacked synthesized record ($\delta^{18}\text{O}_{\text{syn}}$). This was obtained by averaging all the values at each sampling point for the 16 Holocene stalagmite $\delta^{18}\text{O}$ records from 14 caves in the EASM region. In addition, we used a partitioning synthesis approach to assess the reliability of the synthetic record ($\delta^{18}\text{O}_{\text{syn}}$). First, we divided the eastern monsoon region of China into two sub-regions: north and south, with the boundary corresponding to the Qinling-Huaihe River. We then synthesized the stalagmite records for the south and north sub-regions, separately. Finally, we calculated the arithmetic average of the synthesized data for the two sub-regions to produce another synthesized record ($\delta^{18}\text{O}_{\text{S+N}}$).

Results and discussion

Stalagmite $\delta^{18}\text{O}$ records from Chongqing, southwest China

Following previous research (Cai et al., 2010, 2012; Cheng et al., 2012, 2016; Dong et al., 2010; Wang et al., 2005, 2008), our initial premise was that stalagmite $\delta^{18}\text{O}$ records are proxies of EASM intensity, and our results enable this assumption to be tested. Following the sub-division of the Holocene by Walker et al. (2014), 8 and 4 kyr BP are taken as the respective boundaries of the early to middle Holocene and the middle to late Holocene.

In the HF01 stalagmite record from Heifeng Cave in Chongqing (Figure 2), the $\delta^{18}\text{O}$ values are more negative during 11.5–10.0 kyr BP, indicating the gradual strengthening of EASM from the beginning of the Holocene. The values are moderately negative and relatively stable during 10.0–8.5 kyr BP, indicating a comparatively stable EASM, and they are more positive during 8.5–8.0 kyr BP, indicating a weak EASM event. The values are the most negative during 8.0–7.0 kyr BP, in the middle Holocene, reflecting the strongest EASM during the entire Holocene. In the J13 stalagmite record from Jinfo Cave, the $\delta^{18}\text{O}$ values are more negative during 10.2–9.2 kyr BP, and subsequently there is a weak monsoon event lasting for about 1 kyr, indicating an unstable EASM. During 8.1–7.0 kyr BP, in the middle Holocene, there is another interval of more negative values. Thus, the J13 $\delta^{18}\text{O}$ record suggests a strong EASM in both the early and the middle Holocene, with both intervals having a similar duration.

In stalagmite J12 from Jinfo Cave, there is a 2-kyr hiatus in the early Holocene; during 8.0–6.5 kyr BP, the $\delta^{18}\text{O}$ values are stable and more negative. In stalagmite QM09 from Shizi Cave, there is also a hiatus in the early Holocene; during 9.2–8.0 kyr BP, the $\delta^{18}\text{O}$ values oscillate markedly, and during 8.0–6.0 kyr BP, they are relatively negative, indicating a strong EASM.

From the foregoing, it can be concluded that the Holocene stalagmite $\delta^{18}\text{O}$ records from the three caves in Chongqing show a similar trend of variation on the orbital scale, which is in accord with the trend of changing summer insolation in the Northern Hemisphere. On centennial-millennial scales, however, there are substantial differences; for example, the timing and duration of the interval of stable and more negative $\delta^{18}\text{O}$ values for each cave varied during the Holocene. Furthermore, although Jinfo Cave is only 1200 m from Heifeng Cave, their Holocene climatic records are

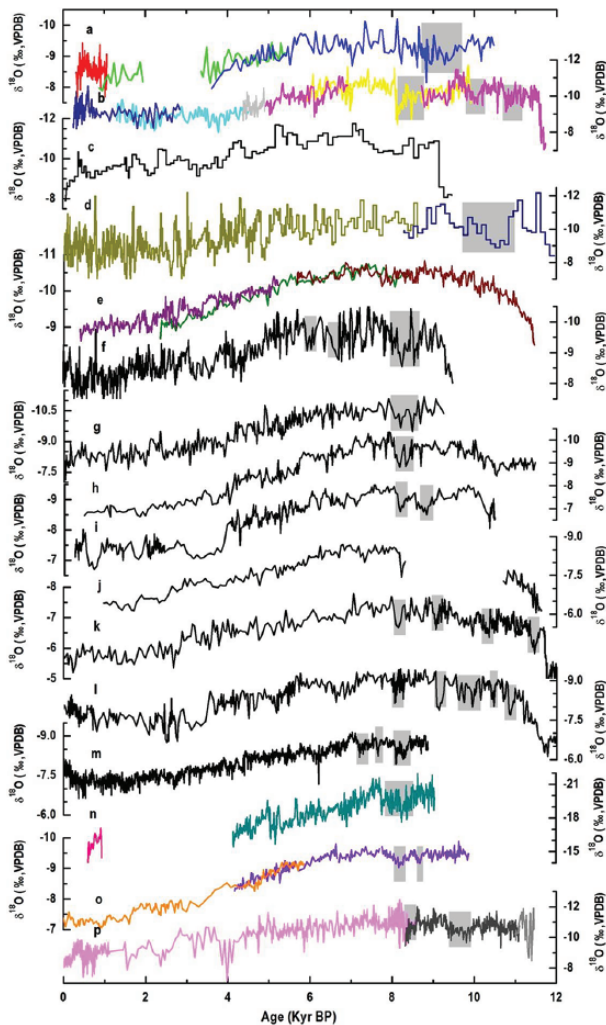


Figure 3. Comparison of Holocene stalagmite $\delta^{18}\text{O}$ records from the Chinese monsoon region.

(a) Nuanhe Cave (NH12, red; NH13, green; MH 15, blue) (Wu et al., 2011); (b) Lianhua Cave (LHD1, blue; LHD3, LT gray; LHD4, yellow; LHD9, cyan; LHD5, magenta) (Dong et al., 2015); (c) Buddha Cave (SF) (Li et al., 2000); (d) Jiuxian Cave (C996-1, yellow; C996-2, blue) (Cai et al., 2010); (e) Sanbao Cave (SB 27, olive; SB10, wine; SB26, purple) (Dong et al., 2010); (f) Heshang Cave (HS4) (Hu et al., 2008); (g) Shizi Cave (QM09) (this study); (h) Heifeng Cave (HF01) (this study); (i) Jinfo Cave (J13) (this study); (j) Jinfo Cave (J13); (k) Lianhua Cave (LH2) (Zhang et al., 2013); (l) Dongge Cave (D4) (Dykoski et al., 2005); (m) Dongge Cave (DA) (Wang et al., 2005); (n) Tianmen Cave (TM18B, pink; TM18A, cyan) (Cai et al., 2012); (o) Shigao Cave (SG1, violet; SG2, orange) (Jiang et al., 2012). (p) Dongshiya Cave (DSY1, LT magenta; LM2 dark gray; DSY9 gray) (Zhang et al., 2018). The vertical gray bars indicate weak EASM events in the early and middle Holocene. Stacked stalagmite records are shown by colors other than black; otherwise black is used.

different on the centennial-millennial scale, which may be attributed to factors other than climate change (Fairchild et al., 2006).

Stalagmite $\delta^{18}\text{O}$ records from elsewhere in China

The variations in the $\delta^{18}\text{O}$ records of the cave stalagmites on a centennial-millennial scale may be influenced by a complex range of factors. In addition to climatic factors (e.g. precipitation, temperature and water source), local factors (e.g. seepage path, karst fissure water, convective cave ventilation and kinetic fractionation) can also influence stalagmite $\delta^{18}\text{O}$ values on a short timescale (Fairchild et al., 2006). All these factors may filter or obscure a common climatic signal within stalagmite records, leading to differences on decadal, centennial and millennial scales (Tan et al., 2009; Zhang et al., 2008). Clearly, therefore, multiple

stalagmite records from different caves are needed to isolate a common climatic signal.

The HS4 stalagmite $\delta^{18}\text{O}$ record from Heshang Cave (Hu et al., 2008) (Figure 3), also in the upper reaches of the Yangtze River, shows a similar trend to the records from Shizi Cave. The HS4 record contains an asymmetrical 'W'-shaped oscillation during 8.8–8.0 kyr BP, with more stable and negative values during 8.0–5.0 kyr BP. The stalagmite $\delta^{18}\text{O}$ records from Nuanhe Cave, in North China (Wu et al., 2011), exhibit substantial oscillations during 10.4–8.2 kyr BP, in the early Holocene, and more stable and negative values during 8.2–5.6 kyr BP, indicating a strong EASM. The records from Lianhua Cave in Shanxi Province (Dong et al., 2015) contain substantial oscillations throughout the early Holocene, indicating the occurrence of a series of centennial-millennial-scale abrupt events; subsequently, during 8.0–6.3 kyr BP, the values are more stable and negative, indicating a strong EASM. The record from Jiuxian Cave (Cai et al., 2010) an initial negative inflection at around 11.5 kyr BP, in the early Holocene; this is followed by a positive $\delta^{18}\text{O}$ trend lasting for about 2 kyr, and then by more negative values during 9.0–4.0 kyr BP. The record from Sanbao Cave (Dong et al., 2010) is relatively uniform throughout the Holocene. The record from Lianhua cave (Zhang et al., 2013) in Hunan Province, southern China, is comparatively negative in the early Holocene, with the most negative values during 9.5–7.0 kyr BP. At Dongge Cave (Wang et al., 2005), the record rapidly becomes negative at the beginning of the early Holocene (11.6–11.0 kyr BP), indicating a strengthening of the EASM, and during 11.0–9.0 kyr BP, there are a series of oscillations suggesting intervals of a weakened monsoon which lasted for 10–100 years. During two intervals, 8–7 and 9.0–8.2 kyr BP, the values are stable and negative.

Stacked stalagmite record ($\delta^{18}\text{O}_{\text{syn}}$)

Comparison of the various stalagmite $\delta^{18}\text{O}$ records from the three caves in Chongqing, and from sites elsewhere in China, reveals differences in the timing and duration of intervals of stable, negative values within the Holocene. Clearly, therefore, no individual cave stalagmite $\delta^{18}\text{O}$ record can be taken to represent variations in the EASM on the centennial-millennial scale. The two synthesized records ($\delta^{18}\text{O}_{\text{syn}}$ and $\delta^{18}\text{O}_{\text{S+N}}$) have a very consistent trend and they are strongly correlated ($R = 0.99$). To further evaluate the reliability of the synthesized records, we compared them with the results of principal components analysis of 7 integrated Holocene stalagmite records (Figure 3b, d, e, h, k, l, and p). The results show that the first component (PC1) captures a large proportion of the variance (78.8% of the total) and the plot of the sample scores on PC1 is well correlated with the synthesized record ($\delta^{18}\text{O}_{\text{syn}}$) ($R = 0.99$). This suggests that the synthesized data are reliable.

These records, which are illustrated in Figure 4, emphasize the common characteristics of the set of Holocene stalagmite records from China. On the orbital timescale, the variation of the synthesized record ($\delta^{18}\text{O}_{\text{syn}}$) clearly tracks changes in Northern Hemisphere summer insolation. Specifically, the record exhibits a gradual trend of increasingly negative values in the early Holocene. Superimposed on this trend are three pronounced negative shifts followed by a positive shift. During 11.6–11.0 kyr BP, the values rapidly become negative, with a moderate negative peak at 11.0 kyr BP, indicating that the EASM gradually strengthened at the beginning of the Holocene. Subsequently, at around 11.0 kyr BP, there is a 'W'-shaped oscillation which lasted for about 0.5 kyr, indicating a weak EASM event. In addition, there are two positive events centered at 9.4 and 8.2 kyr BP, each of which lasted for about 0.3–0.5 kyr. These short-term features suggest an unstable EASM during the early Holocene. These weak monsoon events coincide with

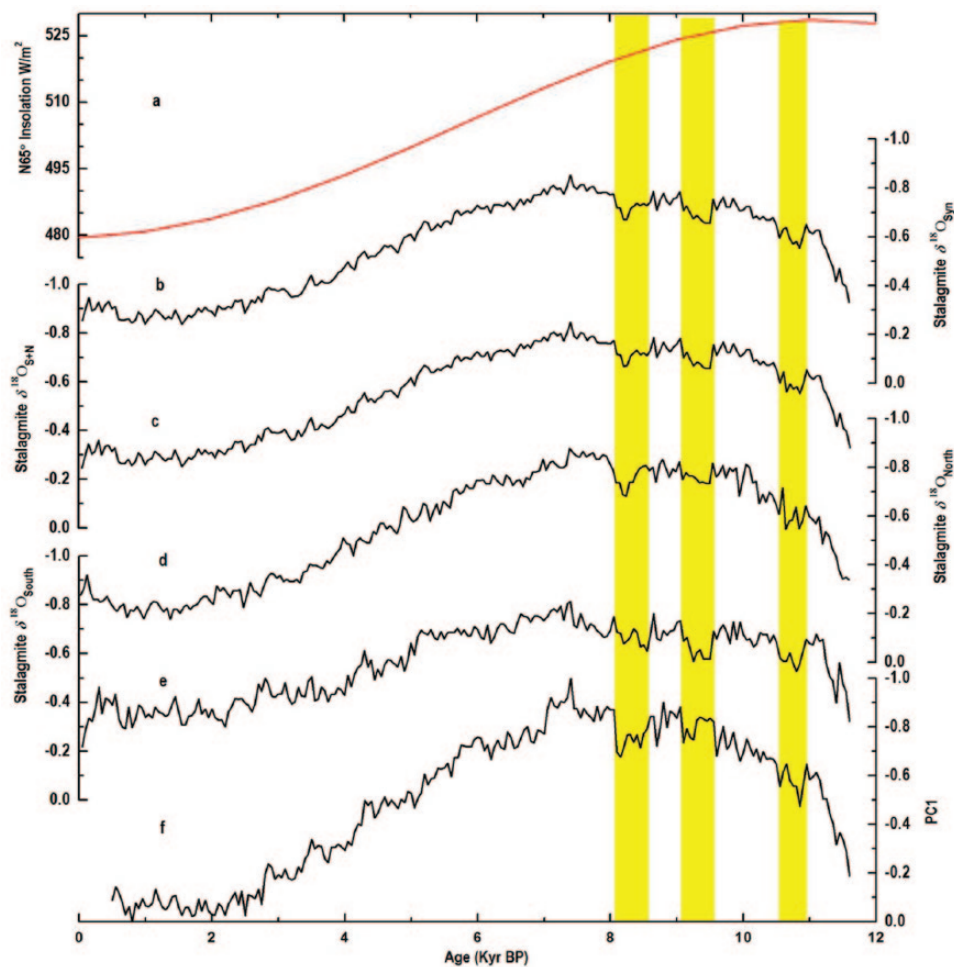


Figure 4. Comparison of stacked stalagmite $\delta^{18}\text{O}$ records and Northern Hemisphere summer insolation. (a) Northern Hemisphere summer insolation at 65°N (Laskar et al., 2004). (b) Stacked stalagmite $\delta^{18}\text{O}_{\text{syn}}$ record. (c) Stacked stalagmite $\delta^{18}\text{O}_{\text{S+N}}$ record. (d) Stacked stalagmite $\delta^{18}\text{O}_{\text{North}}$ record from six caves in northern China: Nuanhe Cave (Wu et al., 2011), Lianhua Cave (Dong et al., 2015), Buddha Cave (Li et al., 2000), Jiuxian Cave (Cai et al., 2010), Sanbao Cave (Dong et al., 2010), and Dongshiya Cave (Zhang et al., 2018). (e) Stacked stalagmite $\delta^{18}\text{O}_{\text{South}}$ record from eight caves in southern China: Heshang Cave (Hu et al., 2008), Shizi Cave (this study), Heifeng Cave (this study), Jinfo Cave (J13) (this study), Lianhua Cave (Zhang et al., 2013), Dongge Cave (Dykoski et al., 2005; Wang et al., 2005), Tianmen Cave (Cai et al., 2012), Shigao Cave (Jiang et al., 2012). (f) Sample scores on the first principal component (PC1) of a principal components analysis of seven integrated Holocene stalagmite records (see Figure 3). The vertical yellow bar corresponds to an interval of weak EASM in the early Holocene.

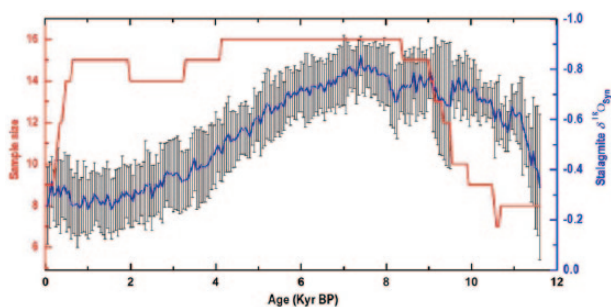


Figure 5. Stacked and normalized Chinese stalagmite $\delta^{18}\text{O}_{\text{syn}}$ record. Black error bars indicates standard deviations.

three cold events evident in the Greenland NGRIP $\delta^{18}\text{O}$ paleotemperature record, at 11.0, 9.3, and 8.2 kyr BP, corresponding to North Atlantic cold events 5, 6, and 8 (Bond et al., 2001; Johnsen et al., 2001). This indicates the covariation of Asian monsoonal fluctuations with climate change at high latitudes of the Northern Hemisphere. The $\delta^{18}\text{O}_{\text{syn}}$ record is relatively stable with moderately negative values during 8.0–6.0 kyr BP, indicating a strong EASM. The values are the most negative during 8.0–7.0 kyr BP, in the middle Holocene, indicating that the

strength of the EASM was at a maximum. During 8.0–6.0 kyr BP, the middle Holocene, the values are 9.31% more negative than in the early Holocene (11.0–8.0 kyr BP).

Two major observations can be drawn from the foregoing. First, the early Holocene EASM was unstable, with several abrupt fluctuations, and second, the EASM was stronger in the middle Holocene than in the early Holocene. These findings differ from the concept of an early Holocene maximum based on stalagmite records proposed by Chen et al., (2016b). Therefore, in terms of the intensity, stability, and duration of the EASM, the stalagmite records exhibit a classical mid-Holocene Optimum. Vaks et al. (2013) and Wang et al. (2004) suggested that phases of stalagmite growth likely correspond to intervals of high rainfall. Our results indicate the continuous growth of stalagmites in all 14 caves during 8.0–5.0 kyr BP (Figures 3 and 5), and in contrast, few stalagmites in these caves grew continuously in the early Holocene and in the later Holocene. This indicates that in general the EASM region was humid during the middle Holocene.

Comparison of the synthesized stalagmite record ($\delta^{18}\text{O}_{\text{syn}}$) with other monsoon records

A comparison of the $\delta^{18}\text{O}_{\text{syn}}$ record with other Holocene records of EASM/precipitation (Figure 6) reveals similar trends of

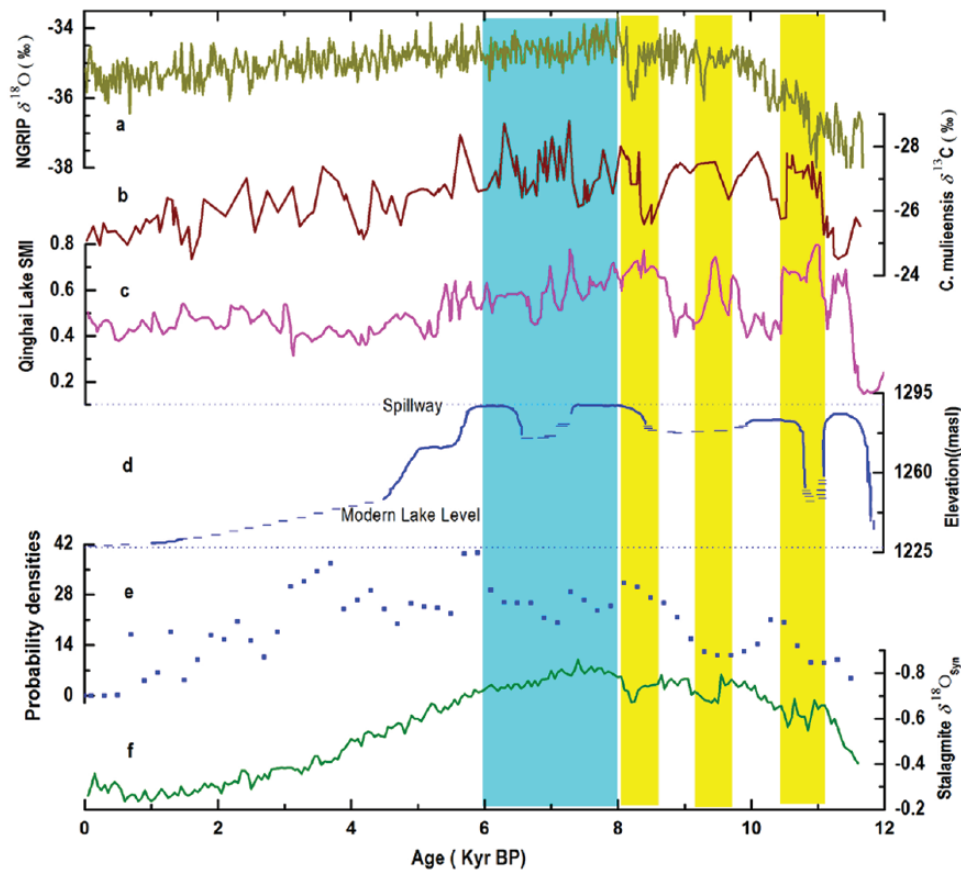


Figure 6. Comparison of a stacked $\delta^{18}\text{O}_{\text{syn}}$ stalagmite record from China with other paleoclimatic records. (a) NGRIP Greenland ice core record (Johnsen et al., 2001); (b) Hongyuan peat $\delta^{13}\text{C}$ record (Hong et al., 2003); (c) Qinghai Lake summer monsoon index (SMI). SMI is non-dimensional and increased SMI values simply represent enhanced summer monsoon intensity (An et al., 2012); (d) Dali lake level (Goldsmith et al., 2017); (e) probability densities of paleosol dates from the Loess Plateau (Wang et al., 2014); (f) stacked synthesized $\delta^{18}\text{O}$ stalagmite record from China (this study). The three vertical yellow bars indicate weak EASM events in the early Holocene that can be correlated to cold events recorded by the Greenland NGRIP paleotemperature record (Johnsen et al., 2001), and the vertical cyan bars denote the timing of the Holocene Optimum.

variation. The Hongyuan peat $\delta^{13}\text{C}$ record from the eastern Tibetan Plateau indicates that the Asian summer monsoon was unstable, with three strong/weak events in the early Holocene (Hong et al., 2003); however, the Asian summer monsoon was relatively stable and strong during 8.0–5.0 kyr BP. The East Asian summer monsoon index (SMI) from Lake Qinghai indicates two intervals of a strengthened EASM in the early Holocene, each of which persisted for only ~ 0.5 kyr (An et al., 2012). The lake-level history of Lake Dali (Goldsmith et al., 2017) suggests that the level increased rapidly in the early Holocene, during which there were two brief episodes of moderate lake-level rise, and that subsequently the lake level fell rapidly; this indicates an unstable EASM in the early Holocene with significant lake level oscillations. The highest lake level was during 8.0–5.8 kyr BP, in the middle Holocene, indicating that the EASM was at its maximum intensity at that time, which is supported by a pollen record from Lake Dali (Xiao et al., 2008). The $\delta^{18}\text{O}_{\text{syn}}$ record exhibits a significant inverse relationship (Figure 7, $R = -0.64$, $p < 0.001$, $N = 232$) with a recent precipitation record from Gonghai Lake in northern China (Chen et al., 2015). The pollen record from Gonghai Lake suggests that EASM rainfall increased gradually from the beginning of Holocene; during 10.2–9.6 kyr BP, there was a moderate EASM strengthening and a humid stage; during 9.6–8.0 kyr BP, there was a transient weakening of the EASM; and the highest precipitation occurred during 8.0–5.3 kyr BP in the middle Holocene. This latter interval coincides with an interval of strong EASM indicated by the $\delta^{18}\text{O}_{\text{syn}}$ record.

Based on the aforementioned observations, it is apparent that the stalagmites records and other monsoon/precipitation records based on lake sediments (An et al., 2012; Chen et al., 2015; Goldsmith et al., 2017), peats (Hong et al., 2003), and paleosols (Wang et al., 2014) exhibit a similar trend during the Holocene. This implies that when the monsoon was relatively strong, a more humid period occurred in the eastern monsoon region of China. Although Chinese stalagmite records exhibit a good consistency across a substantial part of China on the orbital scale (Yang et al., 2014), there are substantial differences in precipitation at different localities (Dayem et al., 2010). Stable isotope records of stalagmites from Wanxiang Cave (Zhang et al., 2008) and Dayu Cave (Tan et al., 2015) reveal a good correlation with local precipitation, but the results from Heshang Cave are inconsistent with the variations of both local precipitation and a drought-wetness index (Hu et al., 2008; Tan, 2009; Xie et al., 2013). The climate simulation results of Pausata et al. (2011) suggest a possible scenario in which, in the eastern monsoon region of China, a negative (positive) shift in precipitation $\delta^{18}\text{O}$ values on a millennial timescale mainly reflects strong (weak) Asian summer monsoon events as a whole, rather than the amount of local rainfall in the individual site. Considering the complex relationship between monsoon intensity and local precipitation (Tan, 2009; Zhang et al., 2018), we cannot simply interpret $\delta^{18}\text{O}$ variations of Chinese stalagmites as local precipitation, but rather as a mean state of summer monsoon intensity, or integrated moisture transport (Cheng et al., 2006, 2012; Johnson and Ingram, 2004).

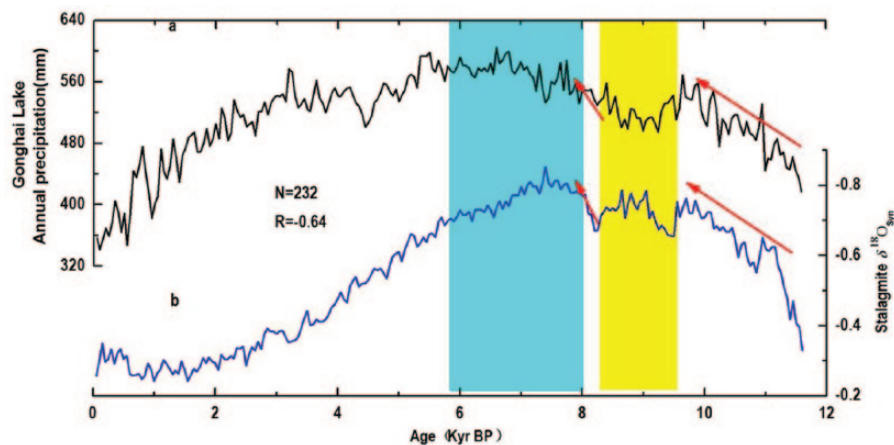


Figure 7. Comparison of a stacked $\delta^{18}\text{O}_{\text{syn}}$ stalagmite record (b) and Gonghai Lake Record (a) (Chen et al., 2015). The vertical yellow bar corresponds to an interval of weak EASM in the early Holocene, and the vertical cyan bar corresponds to the Holocene Optimum.

The early Holocene changes in the EASM on a centennial-millennial scale recorded by geological archives (e.g. loess, lake sediments and stalagmites) are generally different. The pollen record from Qinghai Lake (Shen et al., 2005) does not show significant EASM events, but two episodes of intensified/weakened EASM are evident in the EASM Index from Lake Qinghai (An et al., 2012); in addition, a millennial-scale decrease of the EASM in the early Holocene is evident in the pollen record from Gonghai Lake (Chen et al., 2015). There are also large differences in the number and magnitude of abrupt climatic events in the early Holocene recorded by different stalagmite records. The stalagmite records from Lianhua Cave in northern China suggest at least four episodes of weakened EASM in the early Holocene (Dong et al., 2015), and there is at least one episode of a weakened EASM at Heshang Cave (Hu et al., 2008) and at Heifeng Cave; however, there is no clear record of abrupt climatic events at Sanbo Cave (Dong et al., 2010). The reasons for the inconsistent recording of these abrupt events may include the different geological archives and proxies analyzed, differences in sampling resolution and age uncertainty, and genuine regional climatic differences (An et al., 2012; Chen et al., 2015; Dong et al., 2015, 2010; Hu et al., 2008; Shen et al., 2005). In addition, the evidently unstable nature of the early Holocene climate in China makes it unsurprising that the abrupt climatic events were not recorded consistently across a wide geographical area and in contrasting geological archives.

Despite the evident complexity of EASM fluctuations during the early Holocene, the main trend of Holocene EASM recorded by the stalagmite $\delta^{18}\text{O}$ records in this study is similar to other EASM/precipitation records in China. This confirms the effectiveness of stalagmite $\delta^{18}\text{O}$ records as an indicator of EASM change. Considering the complexity of the factors affecting the stalagmite $\delta^{18}\text{O}$, the climatic significance of the stalagmite $\delta^{18}\text{O}$ needs further study. However, our findings at least indicate that EASM strength/EASM is a very important factor for stalagmites $\delta^{18}\text{O}$ changes in EASM regions, but it is not the only influencing factor.

Conclusion

- We have compared 16 stalagmite $\delta^{18}\text{O}$ records from 14 caves in the EASM region to try to address the controversy regarding the paleoclimatic significance of such records during the Holocene.
- The variation of a stacked Holocene stalagmite $\delta^{18}\text{O}$ record ($\delta^{18}\text{O}_{\text{syn}}$) is consistent with other EASM/precipitation records from China, indicating that stalagmite $\delta^{18}\text{O}$

records are recorders of changes in EASM intensity, rather than local precipitation.

- The stalagmite $\delta^{18}\text{O}_{\text{syn}}$ record is relatively stable and moderately negative during 8.0–6.0 kyr BP, with the most negative interval occurring during 8.0–7.0 kyr BP, in the middle Holocene. Thus, maximum strength and stability of the EASM occurred during the middle Holocene, in accord with the classical view of a middle-Holocene Optimum in China.
- Previous studies have focused on determining whether the early-Holocene EASM in China was strong or weak. However, our results indicate substantial instability of the EASM during the early Holocene, evidenced by a series of abrupt monsoon events on a centennial-millennial scale. Therefore, irrespective of the intensity, duration and stability of the monsoon, the early Holocene was not the EASM maximum or the Climatic Optimum in China.
- Episodes of abrupt strengthening/weakening of the EASM during the early Holocene are inconsistently recorded in different geological archives. This phenomenon may be the major cause of the controversies regarding the pattern of Holocene climate change in China, and it requires further investigation.

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Holocene stalagmite $\delta^{18}\text{O}$, the chronological data, and stacked stalagmite data used to support the findings of this study can be obtained in the supporting information file (available online). All these data will be deposited in the World Data Center repository (<https://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets/speleothem>).

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Supplemental material

Supplemental material for this article is available online.

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