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Highly negative oxygen isotopes in precipitation in southwest China and their significance in paleoclimatic studies

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ABSTRACT

The moisture carried by the Indian summer monsoon (ISM) is increasingly believed to have an important effect on oxygen isotope in precipitation ($\delta^{18}O_p$) in the East Asian summer monsoon (EASM) region. This is mainly based on the spatially coherent variability in the stalagmite oxygen isotopic records ($\delta^{18}O_s$) from both the ISM and EASM regions. Based on the comparison of $\delta^{18}O_s$ records with variable time scales, including the last glacial (36–54 ka BP) and the mid–late Holocene (2–6.5 ka BP), in this paper, we show that the $\delta^{18}O_s$ values in southwest China were much more negative than in the EASM region of east China, and the behavior of modern $\delta^{18}O_p$ values is similar. Detailed analyses demonstrated that the highly negative $\delta^{18}O_s$ and $\delta^{18}O_p$ values in southwest China could not be explained by any of the altitude, latitude, amount, and temperature effects, and therefore the only interpretation for this phenomenon was might the different moisture sources. The different major moisture sources for southwest and east China were supported by further analyses of the deuterium excess (*d-excess*) parameter of modern $\delta^{18}O_p$ and δD values for both the ISM and EASM regions. The results suggested that the moisture sources for the ISM and EASM regions were might essentially different. Our findings could contribute to a better understanding of the paleoclimatic history in the ISM and EASM regions and their possible interactions.

1. Introduction

As two important subsystems of the Asian monsoon (Huang and Tao, 1986), the East Asian summer monsoon (EASM) composed of a tropical monsoon and a subtropical monsoon mainly dominated southeast China, the middle and lower reaches of the Yangtze River, and north China. The major dominating regions of the Indian summer monsoon (ISM) as a tropical monsoon in China are the southwest corner (typically, Yunnan Province) and the south Tibetan Plateau (Wang and Lin, 2002). Meanwhile, Guizhou and Guangxi provinces in south China are considered as the region commonly influenced by both the EASM and ISM (Wei and Lin, 1994; Wei and Gasse, 1999). Modern meteorological studies have demonstrated that these two subsystems are different, and their relationship is complicated (Huang and Tao, 1986; Wang and Lin, 2002).

The paleoclimatic histories of the ISM and EASM regions and their possible interactions have been widely studied and intensely debated (e.g., Wang et al., 2003; Hong et al., 2005; Zhou et al., 2008; Han et al., 2010; Wang et al., 2010; Li et al., 2014; Allu et al., 2015). The typical and influential viewpoints are as follows. (i) Based on the lake level, pollen, eolian deposit evidence and similar data, in combination with modeling results, the Holocene optimum, as defined by the peak summer monsoon precipitation, was proposed that asynchronous occurred in China, with a withdraw trend from north to southeast China (EASM region), but occurred earliest in southwest China (ISM region; Wu et al., 1994; An, 2000). (ii) Based on a comparison between the peat α-cellulose $\delta^{13}C$ data from the Hani site in northeast China (which are believed to indicate a record EASM intensity) and from the Hongyuan site in southwest China (which are believed to indicate a record ISM intensity), inverse phase oscillations between the EASM and ISM have been suggested on the interannual-to-orbital time scales during the past 12,000 years (Hong et al., 2005; Xu et al., 2006). (iii) Based on synthetic analyses of modeling results and stalagmite paleoclimatic records, it has been proposed that the relationship between the EASM and

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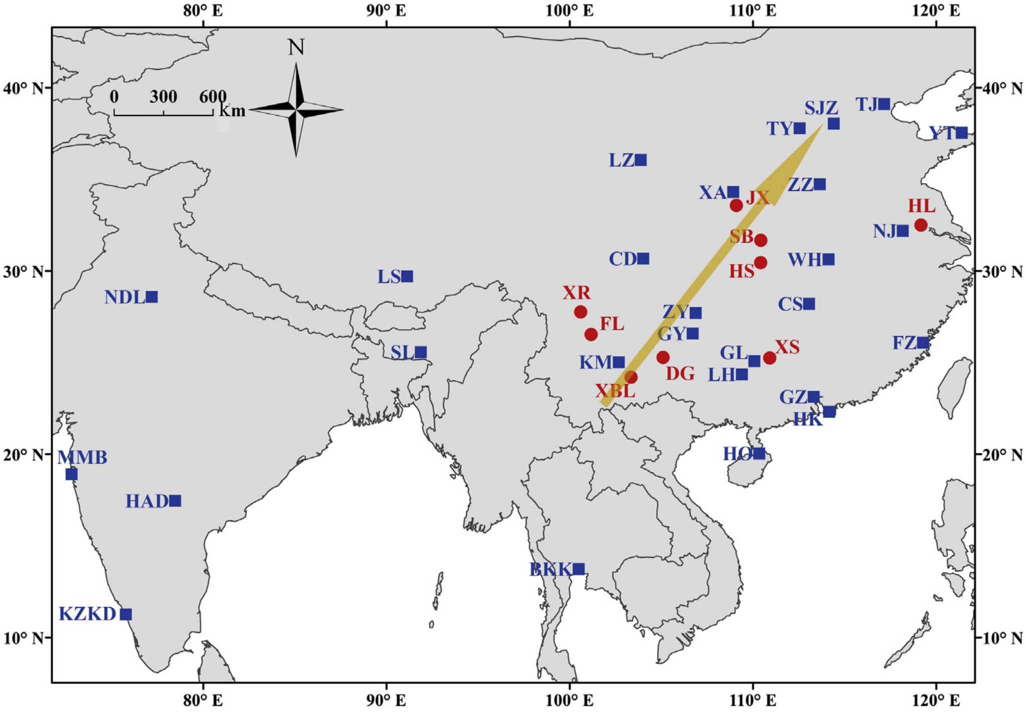

Fig. 1. Locations of the selected caves (red dots) and weather stations (blue squares); the codes for the caves and stations are the same as in Tables 1 and 2; the light-yellow arrow indicates the possible moisture route proposed in a previous study (Liu et al., 2015). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

ISM regions is more complicated than in-phase or anti-phase, and it might vary with different time scales (Li et al., 2014).

High-quality and precisely dated stalagmite oxygen isotopic records ($\delta^{18}O_s$) have been widely reported for both ISM and EASM regions in the last 15 years (e.g., Wang et al., 2001, 2005, 2008; Fleitmann et al., 2003; Dykoski et al., 2005; Hu et al., 2008; Cheng et al., 2009; Dong et al., 2010; Kotlia et al., 2012; Muangsong et al., 2014; Cai et al., 2015; Tan et al., 2015; Han et al., 2016), and these records were soon used in discussions on the relationship between ISM and EASM. Using a numerical climate model with an embedded oxygen isotope model, the paleoclimatic conditions and oxygen isotopic composition of precipitation ($\delta^{18}O_p$) in both ISM and EASM regions during the last glacial maximum interval and the Heinrich 1 event have been simulated and compared with the relevant $\delta^{18}O_s$ records, and the results have demonstrated that the $\delta^{18}O_s$ records from southeast China (EASM region) reflected the ISM intensity rather than the EASM precipitation (Pausata et al., 2011). Recently, the $\delta^{18}O_s$ records from both the ISM and EASM regions, and the paleoclimatic records from the EASM region, particularly those from north China, have been comprehensively compared. The results demonstrated spatially coherent variabilities and statistically good correlations on different time scales in the $\delta^{18}O_s$ records; however, the most negative $\delta^{18}O_s$ stage during the early Holocene in southeast China is apparently different from the most humid stage during the mid-Holocene in north China (EASM region). Therefore, it has been concluded that the $\delta^{18}O_s$ in the EASM region was mainly controlled by the rainfall variability in the ISM region via the remaining moisture carried by the ISM that flowed out to the EASM region (Yang et al., 2014; Liu et al., 2015).

The $\delta^{18}O_s$ records from both the ISM and EASM regions show spatially coherent variabilities and statistically good correlations, particularly the high resolution Holocene $\delta^{18}O_s$ records (e.g., Fleitmann et al., 2003; Dykoski et al., 2005; Hu et al., 2008; Dong et al., 2010), which may not be adopted as convincing evidence for the assumption that the $\delta^{18}O_p$ signal in the EASM region comes from the ISM region. Unlike the Holocene, the most recently reported $\delta^{18}O_s$ records from the central China showed an overall opposite trend to that from India for the last 98 years (Tan et al., 2015), and to that from southern India for the period of ca. 108–99 ka BP (Allu et al., 2015). That is, the moisture sources for the ISM and EASM regions still require additional studies. In this paper, based on the comparison of $\delta^{18}O_s$ records from southwest China (ISM region) and from east China (EASM region), in combination with the analyses of modern $\delta^{18}O_p$ from both ISM and EASM regions, we show the different moisture sources for the two regions.

2. Data and methodology

Traditionally, Yunnan Province in the southwest corner of China has been widely accepted as a typically dominating area of the ISM (Cai et al., 2006, 2015; An et al., 2011; Chen et al., 2014). Consequently, the $\delta^{18}O_s$ records from three caves located in Yunnan Province have been selected in this work as representative of the variation of the past $\delta^{18}O_p$ values in this area. These are: the Xianren (Zhang et al., 2006), Xiaobailong (Cai et al., 2006) and Fulu (Zhu et al., 2015) caves. Correspondingly, based on the time span of the $\delta^{18}O_s$ records from the three caves, the $\delta^{18}O_s$ records from another six caves from the EASM region were selected for comparison. These are the Hulu (Wang et al., 2001), Dongge (Wang et al., 2005), Xiangshui (Cosford et al., 2008), Heshang (Hu et al., 2008), Jiuxian (Cai et al., 2010), and Sanbao (Dong et al., 2010) caves. Additional detailed information of the nine caves is shown in Table 1, and their spatial distribution is shown in Fig. 1.

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