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Asynchronous Holocene Asian monsoon vapor transport and precipitation

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ABSTRACT

Millennial-scale variations in the Asian monsoon vapor transport are always associated with long-term changes in monsoon rainfall according to the conventional understanding. However, recent advances in monsoon studies suggested that regional monsoon rainfall has different responses to monsoon vapor transport. This paper presents a comparison between monsoonal vapor and precipitation records along the path of the Asian summer monsoon vapor transport. Pedogenic carbonate $\delta^{18}O$ values in both surface sediment and Holocene eolian and lacustrine sediments from the Shiyang River drainage basin were used to investigate the variations of the Asian monsoon vapor transport. Meanwhile, Holocene lake-level changes of the terminal lake were reconstructed to reflect the monsoon precipitation variability. The results show that millennial-scale monsoon vapor transport is in accordance with low-latitude summer insolation, while the increasing summer monsoon rainfall during the early Holocene lags the monsoon water vapor transport. In addition, the relatively cold oceans left over from glacial periods and slow melting of ice sheets may temper the onset of the rainfall. These findings can provide insights into the interpretation of the asynchronous Holocene records from lakes and caves in East Asia.

1. Introduction

The records of millennial-scale Asian summer monsoon commonly associate the Asian summer monsoon vapor transport with the amount of monsoon rainfall based on the hypothesis that summer monsoon-sourced moisture flux is positively correlated with the total precipitation in monsoonal Asia (Maher, 2008; Cheng et al., 2009; Liu et al., 2014). Therefore, speleothem and lake oxygen isotope records ($\delta^{18}O$), the robust indicators of vapor sources and transport processes, have been widely used to reconstruct Holocene variations of monsoon rainfall in East Asia (Hu et al., 2008; Zhang et al., 2011). However, recent observational analysis and isotope modelling studies suggested that monsoonal East Asia has different responses to vapor transport from Indian monsoon, and more Indian monsoon vapor transport corresponds to less rainfall in the middle and lower reaches of the Yangtze River (Zhang, 2001; Zhou and Yu, 2005). Furthermore, some scientists have challenged the hypothesis that the oxygen isotope records are closely related to regional precipitation in monsoonal Asia. Maher (2008) pointed out that correlations between rainfall isotopic composition and rainfall amount at the present day in monsoonal Asia appear weak and spatially variable; Chen et al. (2015) indicated that speleothem $\delta^{18}O$ in southern China does not reflect the local rainfall variability in the cave region of southern China.

In order to examine the conventional understanding that millennial-scale variations in the Asian monsoon vapor transport are closely correlated with long-term changes in monsoon rainfall, as well as test the hypothesis of the relationship between the oxygen isotope records and regional precipitation, this paper presents a comprehensive pedogenic carbonate $\delta^{18}O$ record including surface sediment, eolian and lacustrine sediments sequences along the vapor transport path (Fig. 1). Holocene lake-level changes have been verified by lake-level simulations in showing Holocene monsoon precipitation variability in the study area (Li and Morrill, 2010, 2013); therefore, lacustrine sediment records were used to reconstruct monsoon precipitation. Snapshot isotopic simulations in TRACE model have verified millennial-scale monsoon vapor transport to the study area. Fig. 1 indicates precipitation weighted summer (JJA) $\delta^{18}O$ (‰) distribution difference between 6 ka and 1 ka in East Asia (Liu et al., 2014). Ninety-one surface sediment samples were sampled for analysis of pedogenic carbonate $\delta^{18}O$ values in order to verify the impact of the vapor transportation. Two Holocene eolian sedimentary sequences, Huangyanghe a (HYH a) and Huangyanghe b (HYH b), and two Holocene lacustrine sedimentary sequences, Qingtuhu01 (QTH01) and Qingtuhu02 (QTH02), were selected and continuously sampled for carbonate $\delta^{18}O$ and proxy analysis to imply long-term changes of the Asian summer monsoon precipitation and vapor transport. In addition, Holocene Asian summer monsoon isotopic records and

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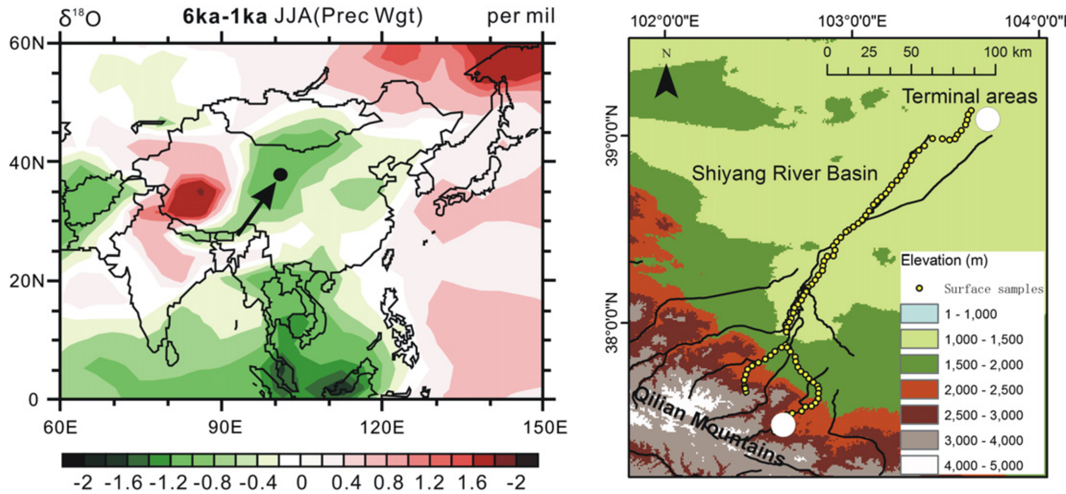

Fig. 1. The precipitation weighted summer (JJA) $\delta^{18}O$ (‰) distribution difference between 6 ka and 1 ka in East Asia (Left, Liu et al., 2014). The black circle indicates the location of study area. Map shows latitudes, longitudes and elevations of the study area (Right). The small yellow circles show the sampling sites of surface sediments and two white circles indicate sampling sites for Holocene eolian and lacustrine sedimentary sequences.

precipitation simulations were compared with the reconstructions in order to explore millennial-scale summer monsoon dynamics.

2. Site description

The study area in the northeast of the Qinghai-Tibet Plateau is located at the transition area between China monsoon region and the plateau (Fig. 1). Summer climate is mainly affected by the Asian summer monsoon and westerly winds, alternatively. Vertically integrated water vapor flux for modern summer indicates that strong monsoon flow brings abundant vapor there for summer precipitation (Li et al., 2012). Winter climate is largely controlled by the cold and dry northwesterly winter monsoon system with little precipitation, while the summer monsoon is the main source for its summer precipitation. Therefore, it is an ideal place to study millennial-scale variations in the Asian monsoon vapor transport and rainfall using pedogenic carbonate $\delta^{18}O$ values. There were collected surface sediment samples from various vegetation sites and altitudinal vegetation zones of the Shiyang River drainage system in the Eastern Qilian Mountains, where evaporation is significantly different in the upper, middle and lower reaches. The lower reaches of the Shiyang River is at an altitude of approximately 1300–1500 m belonging to the northern warm and dry area, with an annual rainfall less than 150 mm (Li et al., 2009). Quaternary alluvial and lacustrine sediments were continuously deposited and a Holocene paleo-lake was formed there. The sampling sites for Holocene eolian sedimentary sequences belong to the alpine semi-arid zone with an altitude of 2000–5000 m, annual rainfall of 300–600 mm, and annual evaporation of 700–1200 mm (Li et al., 2009).

3. Materials and methods

Ninety-one surface sediment samples were collected along the Shiyang River at elevations between 1290 and 3000 m. Fig. 1 indicates the sampling sites for all the surface samples and Fig. 2 shows landscapes of the lower, middle and upper reaches from the drainage system. We chose the surface sampling sites that are less influenced by modern human activities and can indicate original vegetation and landscapes. Supplementary Fig. 1 shows two photos which illustrate lithology of two Holocene sedimentary sequences Huangyanghe (HYH) and Qingtuhu (QTH). Eolian sedimentary sequences HYH a (37°25′N 102° 36′E, Altitude: 2447 m, Depth: 3.20 m) and HYH b (37°25′N 102°36′E, Altitude: 2454 m, Depth: 3.20 m) are located on the terrace of the Haxi River, a tributary of the Shiyang River, which were sampled at 2 cm interval, yielding 160 samples for proxy analysis (Fig. 1). Lacustrine sedimentary sequences QTH01 (39°03′N, 103°40′E, Altitude: 1309 m, Depth: 6.92 m) and QTH02 (39°03′N, 103°40′E, Altitude: 1309 m, Depth: 7.36 m) are located at the dried terminal lake. QTH01 was sampled at 2-cm intervals from lacustrine sediment layers and at 5-cm intervals otherwise, resulting in a total of 292 samples, and QTH02 was sampled at 2-cm intervals. Pedogenic carbonate $\delta^{18}O$ values were measured on a Finnigan-MAT 252 Mass Spectrometer from Chinese Academy of Sciences. Grain size distribution of all samples was measured by the Malvern Mastersizer 2000 particle analyzer that automatically yields the percentages of clay-, silt- and sand-size fractions, as well as median, mean and mode sample diameters. Organic carbon, pollen concentrates and shells were chosen for radiocarbon dating at Radiocarbon Dating Laboratory of Lanzhou University and Radiocarbon Dating Laboratory of Beijing University (Table S1). The evolution of atmospheric water isotopes ($\delta^{18}O$) was simulated by Liu et al. (2014) using the isotope-enabled atmospheric component model of the CCSM3 CAM3 (T31 resolution). TRACE (Transient Climate Evolution, CCSM3 T31 resolution) experiment from the National Center for Atmospheric Research was chosen to calculate the Holocene Asian summer monsoon index (Liu et al., 2014; Li and Morrill, 2015). The Asian summer monsoon index, which is characterized by enhanced southerly winds in eastern China, an increased rainfall in northern China, and weakly reduced rainfall in southern China, was measured as the averaged summer meridional surface wind in East China (V850 JJA, 110°E 120°E; 27°N 37°N) (Liu et al., 2014).

4. Results

Fig. 2 shows pedogenic carbonate $\delta^{18}O$ (‰) values from surface sediment samples at various elevations, as well as photos of landscapes from the lower, middle and upper reaches of the drainage system. Pedogenic carbonate $\delta^{18}O$ (‰) values are generally scattered between −6‰ and −10‰, with most values stabilizing at around −8‰, which are relatively consistent with $\delta^{18}O$ (‰) values from modern Asian summer monsoon precipitation in north China (Deng et al., 2012). It is worth noting that there are a few changes in pedogenic carbonate $\delta^{18}O$ (‰) values along with changes in altitude. Vertical zones are obvious in the study area, so that evaporation in lower and arid lands is much higher than that in the upper reaches (Fig. 2). The results show that pedogenic carbonate $\delta^{18}O$ (‰) values from surface sedimentary samples are mainly controlled by precipitation, with few impacts from