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Continued obliquity pacing of East Asian summer precipitation after the mid-Pleistocene transition

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ABSTRACT

Records from natural archives show that the strength of the East Asian summer monsoon (EASM) strongly depends on the orbital configuration of the Earth. However, the dominant orbital cycles driving EASM have been found to be spatially different. Speleothem stable oxygen isotopic records from southern China, which are believed to reflect large-scale changes in the Asian monsoon system, are dominated by climatic precession cycles. Further north, on the Chinese Loess Plateau (CLP), loess-and-paleosol sequences, which are argued to be controlled by monsoon intensity, are in pace with global ice volume changes dominated by obliquity, and after the mid-Pleistocene transition by 100-kyr cycles. To understand these critical discrepancies, here we apply a novel proxy based on the trace metal compositions of pedogenic carbonate in the eolian deposits on the CLP to reconstruct summer precipitation over the last 1.5 million years. Our reconstructions show that summer precipitation on the CLP is dominantly forced by obliquity not in pace with the ice-volume-imprinted loess-paleosol sequences before and after the mid-Pleistocene transition or with the precession-paced speleothem oxygen isotopic records. Coupled with climate model results, we suggest that the obliquity-driven variations of summer precipitation may originate from the gradient of boreal insolation that modulates the thermal contrast between the Asian continent and surrounding oceans.

1. Introduction

The East Asian Summer Monsoon (EASM) is an important component of the Asian monsoon system that brings a large amount of moisture to middle and high latitudes of Asian continent and thus influences the livelihood of hundreds of millions of people. Knowledge of how the EASM has evolved in the geological past and understanding the underlying dynamics is crucial to predict its future variability under the very likely scenario of global warming (Wang et al., 2012).

Different proxy archives have suggested very different patterns of orbital scale variation in the EASM (An et al., 2011; Caley et al., 2013; Clemens et al., 2010; Thomas et al., 2014). On the one hand, the alternations of loess and paleosol layers in the eolian deposits on the Chinese Loess Plateau (CLP), which can be accurately traced by magnetic susceptibility (An et al., 1990), show strong glacial cyclicity (Sun et al., 2006). The paleosol layers with higher magnetic susceptibility are thought to be produced by stronger pedogenesis due to the enhanced precipitation during the interglacial periods compared to the loess layers of glacial periods (Zhou et al., 1990). Other proxies (Chen et al., 1999; Liu et al., 2005) that were used to reflect the intensity of the EASM in eolian deposits on the CLP generally show similar pattern as the magnetic susceptibility that is in pace with global ice volume changes dominated by obliquity, and after the mid-Pleistocene transition by cycles of ∼100 thousand years (kyrs). The glacial–interglacial pattern of EASM suggested by the loess-paleosol sequences has also been inferred from lacustrine sediments (An et al., 2011; Ao et al., 2012). Mechanisms proposed for the inferred glacial–interglacial pattern of the EASM include the shifting position of the rainfall

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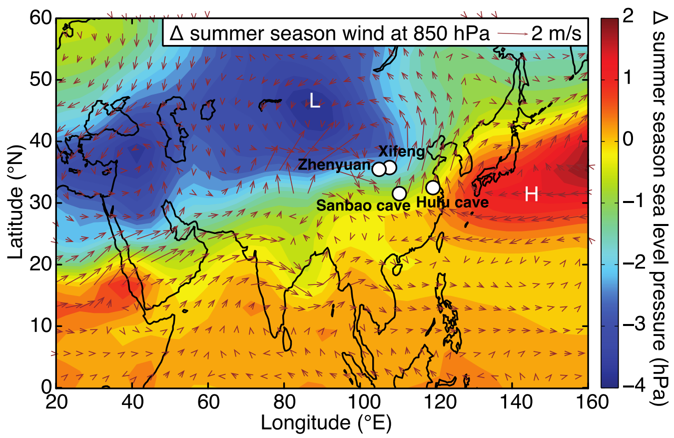

Fig. 1. Model results of summer season sea-level pressure and 850 hPa horizontal wind fields between high and low obliquity. Results denote difference of the 300-yr average results of July, August and September between the 24.5° obliquity run and the 22.1° obliquity run. L and H label the centers of low and high sea-level pressure of the present average summer climatology. Also labeled are study sites on the CLP and the Sanbao and Hulu cave.

belt or the exposure of the continental shelf in response sea-level lowering caused by increasing Northern Hemisphere ice volume (Liu and Ding, 1998), bi-hemispheric forcing (An et al., 2011; Caley et al., 2013), and influence of the atmospheric CO_2 concentration (Lu et al., 2013).

The inferred glacial–interglacial pattern of the EASM, however, has been challenged by the cave deposits in southern China, whose stable oxygen isotopic compositions reveal a dominance of climatic precession cycles of ∼23 kyrs (Cheng et al., 2009; Cheng et al., 2016; Wang et al., 2008). Though highly debated, it is generally accepted that the speleothem $\delta^{18}O$ records in southern China reflect large-scale changes of Asian monsoon (Cheng et al., 2016). The dominance of precession cycles in speleothem $\delta^{18}O$ has also been seen in other records from tropical monsoon systems globally (Cheng et al., 2012), which collectively suggests that low latitude insolation and thus the inter-tropical convergence zone (ITCZ) regulates the intensity of monsoonal circulation (Cheng et al., 2012; Yancheva et al., 2007).

It has been suggested that the discrepancies between loess-paleosol sequences and the speleothem oxygen isotopic records may reflect the possible spatial difference on the orbital forcing of summer monsoon intensity (Ao et al., 2012). However, the CLP is only ∼500 km north of the Sanbao cave (Fig. 1), where most of the long-term speleothem records were generated (Cheng et al., 2009, 2016; Wang et al., 2008). It is very unlikely that the EASM, a large-scale climatic system, behaves differently within such a short distance. Instead, the discrepancies between the loess and speleothem records may reflect the fact that most of the current proxies are measures of more processes than the intensity of the EASM alone.

In the loess records, a key factor that changes considerably during glacial–interglacial cyclicity is the strength of the winter monsoon (An et al., 1991). During interglacial periods, a weaker winter monsoon brings less and finer dust to the CLP, which consequently lowers depositional rates to about a quarter of the rates during glacial dust deposition. A lowered rate of deposition increases the time available for pedogenesis. The coincident smaller grain sizes of the transported dust (Prins et al., 2007) increases the reactive surface for pedogenic alteration and lowers the permeability of the soils, so that less water is needed for soil formation. In addition to the weaker winter monsoon bringing less and finer dust, higher temperature and pCO_2 (Petit et al., 1999) during interglacial stages may also have contributed to the stronger pedogenesis of paleosol layers through the kinetics of chemical weathering and biotic activities.

In the cave archives, considerable debate remains on interpretation of the speleothem $\delta^{18}O$ records. The amount effect was initially employed to establish the link between the strength of the Asian monsoon and the speleothem $\delta^{18}O$ records (Yuan et al., 2004). As demonstrated by several studies (e.g. Liu et al., 2014; Cheng et al., 2009; Clemens et al., 2010), the amount effect caused by local summer precipitation amount can hardly explain the $\delta^{18}O$ of rainwater in the cave sites. It is more likely that the upstream processes exert stronger control on speleothem $\delta^{18}O$ than local precipitation amount (Caley et al., 2014; Liu et al., 2014). Changing precipitation seasonality and moisture sources may also contribute to the speleothem $\delta^{18}O$ signals (Clemens et al., 2010; Maher and Thompson, 2012; Orland et al., 2015). Nevertheless, all of these influencing factors favor the interpretation of $\delta^{18}O$ as a reflection of the hydrologic processes and circulation regime over a large part of the Indo–Asian region but not necessarily the strength of the EASM.

Quantitative reconstruction of summer precipitation in East Asia is critical to solve the puzzle regarding the variation of the EASM. Records of the EASM in the geological archives have sought to reconstruct the amount of precipitation since other monsoon characteristics, such as the velocity of southerly winds, are not typically preserved in the sedimentary archives. The best place of such record is in northern China (Chen et al., 2015; Rao et al., 2016), where the precipitation amount is principally controlled by the strength of the EASM (Ding et al., 2008).

A new method has been developed recently to reconstruct intensity of precipitation based on the incorporation of trace metals into microcodium, which is a very pure, pedogenic form of carbonate that precipitates in eolian deposits on the CLP (Li and Li, 2014). The amount of strontium and magnesium incorporated into microcodium from the soil solution is determined by local precipitation (Li and Li, 2014). Lower intensity and frequency of precipitation results in a higher proportion of calcium extracted from the soil solution by the precipitation of secondary carbonates (Li and Li, 2014). This leaves the soil solution with higher strontium to calcium ratio (Sr/Ca) and magnesium to calcium ratio (Mg/Ca) due to the low partition coefficients ($\ll 1$) of strontium and magnesium in calcite. Lower precipitation therefore results in higher Sr/Ca and Mg/Ca ratios stored in microcodium (Li and Li, 2014). Thus, Sr/Ca and Mg/Ca ratios of microcodium can be used to reconstruct precipitation quantitatively.

In this study, we first show that microcodium Mg/Ca ratio is less suitable as a precipitation proxy because of its potential dependence on temperature, calcification rate, and composition of the original soil solution. Oxygen isotopic compositions of microcodium collected from Holocene soils suggest that microcodium is more likely to be formed during summer monsoon seasons. We then establish a 1500-kyr-long summer precipitation record on the CLP based on the Sr/Ca ratios of microcodium with updated calibration equation. Two parallel reconstructions covering the last 500 thousand years are performed to test the reliability of microcodium Sr/Ca proxy as a regional measure of summer precipitation. Moreover, sensitivity experiments forced by variations of orbital parameters are conducted using a general circulation model of intermediate complexity to test the sensitivity of the EASM to orbital forcing. Coupling our geochemical records with model results, we highlight the underestimated role of obliquity in regulating the EASM variability.