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Astronomical and glacial forcing of East Asian summer monsoon variability

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ABSTRACT

The dynamics of glacial–interglacial monsoon variability can be attributed to orbitally induced changes in summer insolation and internal boundary conditions. However, the relative impacts of astronomical and internal factors on East Asian summer monsoon variability remain controversial. Here we combine proxy data and model results to evaluate the response of East Asian summer monsoon change to these forcings. $\delta^{13}C$ of loess carbonate, a sensitive summer monsoon proxy from the western Chinese Loess Plateau, demonstrates coexistence of distinct 100-, 41- and 23-ka periods, in contrast to precession-dominated speleothem $\delta^{18}O$ records in South China. Model results indicate that insolation, ice and CO_2 have distinct impacts on summer precipitation changes in East Asia, whereas their relative impacts are spatially different, with a relatively stronger insolation effect in south China and a more dominant ice/CO_2 influence in north China. Combined proxy data and model results indicate that East Asian summer monsoon variability was induced by integrated effects of summer insolation and changing boundary conditions (e.g., ice sheets and CO_2 concentration). Our proxy-model comparison further suggests that gradual weakening of the summer monsoon related to slowly decreasing summer insolation at astronomical timescales will be likely overwhelmed by the projected ongoing anthropogenic CO_2 emissions.

1. Introduction

Investigating the hydrological cycle is essential for a sustainable Future Earth, because water plays a critical role in global ecological and social systems. Monsoon circulation, as a primary driver of hydrological changes in the low-to-mid latitudes of both hemispheres (Webster et al., 1998; Wang and Ding, 2008; Wang, 2009; Guo et al., 2012; Liu et al., 2013; An et al., 2015), can seriously impact food production, water supply, and natural hazards through severe flood and drought events (Ding and Chan, 2005; Huang et al., 2007). Therefore, understanding monsoon variability from the natural past to the anthropogenic future is critical for both scientific communities and policy makers. Investigation of the natural variability and dynamics of monsoon-related hydrological changes has improved greatly through paleoclimate modeling and data-model integration studies over past decades (e.g., Kutzbach and Street-Perrott, 1985; Kutzbach and Guetter, 1986; Prell and Kutzbach, 1992; Braconnot et al., 2007; Kutzbach et al., 2008; Liu et al., 2014). However, assessing the relative importance of astronomical and glacial factors on monsoon variability remains challengeable due to varied sensitivity of both models and proxies to these forcings (Ding et al., 1995; Wang et al., 2008b; Lu et al., 2013; Liu et al., 2014).

Although monsoon circulation is often defined as a seasonal change in prevailing wind directions, many monsoonal regions also experience large seasonal differences in rainfall as well (Webster

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et al., 1998; Wang and Ding, 2008). Geologically, many proxy indicators of paleomonsoon variability reflect some aspect of changes in rainfall and wind, such as Chinese loess and speleothem records (e.g., Maher and Thompson, 1995; An, 2000; Wang et al., 2008b; Cheng et al., 2009; Liu et al., 2014). Notably, these monsoonal proxies display a considerable range of variability in amplitude, phasing (timing), and relative concentrations of variance within the primary frequency bands associated with three earth's orbital parameters (eccentricity, obliquity, and precession) (e.g., Clemens et al., 2010; An et al., 2011, 2015; Wang et al., 2014). For example, most loess-based proxies are characterized by distinct glacial–interglacial variations with a dominant 100-ka cycle over the last 800 ka, implying a strong coupling to change in ice-sheet volume (Ding et al., 1995; Liu et al., 1999). In contrast, speleothem $\delta^{18}O$ shows a dominant 23-ka cycle, suggesting a direct link to insolation forcing (Wang et al., 2008b; Cheng et al., 2009, 2012). More recently, further analysis of the spelethom records to ice-sheets and insolation forcing indicates a distinct influence of the ice volume change on the $\delta^{18}O$ variability (Caballero-Gill et al., 2012; Thomas et al., 2014; Cai et al., 2015). Different responses of these proxies make it challenging to pin down the relative sensitivity of Asian summer monsoon change to insolation and glacial forcing.

A robust evaluation of the glacial/insolation impacts on monsoon changes has been made using comprehensive data-model comparisons (e.g., Kutzbach and Street-Perrott, 1985; Liu et al., 2003, 2014; Braconnot et al., 2007, 2012; Yin et al., 2009, 2014; Weber and Tuenter, 2011; Eagle et al., 2013). Here we present a sensitive summer monsoon proxy generated from two high-resolution loess sequences on the northwestern Chinese Loess Plateau (CLP), which demonstrates strong sensitivity of summer monsoon variability to changing insolation and glacial boundary conditions. The relative impacts of insolation, ice and CO_2 on East Asian summer monsoon variability were evaluated using sensitivity experiments with the Community Climate System Model 3 (CCSM3) (Collins et al., 2006; Meehl et al., 2006). Further comparison of paleoclimate data with modeling results indicates that insolation, ice and CO_2 have varying contributions to summer precipitation changes in East Asia.

2. Monsoonal setting in East Asia

Monsoon circulation is characterized by seasonal changes in wind direction and precipitation (Webster et al., 1998). Today, monsoonal wind and precipitation are highly seasonal in East Asia. In summer (hereafter referred to as the rainy season from May to September), warm and humid air originating from low-latitude oceans is transported northwestward up to the China–Mongolia boundary, resulting in strong monsoonal precipitation in East Asia (Gao et al., 1962). The northern boundary of the summer monsoon front roughly corresponds to the isohyetal line of mean summer precipitation (SP) around 1 mm/day (Fig. 1a). From a modern meteorological perspective, changes in southerly wind intensity, sea level pressure and summer precipitation within a certain domain can be employed as monsoonal proxies (Wang et al., 2008a). However, monsoonal precipitation is highly variable in East Asia because of meridional shifts in the rain belt linked to variability of the North Pacific Subtropical High (Ding and Chan, 2005), leading to a demarcation of climate regimes between north and south China at ~33°N (Ding and Chan, 2005; Ding et al., 2008). Over the past 50 years (1960–2010), SP has decreased in most parts of north China, but increased evidently in southeast China (Fig. 1b), implying that the SP change cannot be used straightforward to indicate the summer monsoon intensity.

Among available monsoon proxies, seasonality of wind and precipitation changes are two widely used indicators to define the tempo-spatial variation of the summer monsoon intensity (Li and Zeng, 2002; Wang and Ding, 2008). However, correlation between monsoonal winds and precipitation is complicated in East Asia (Fig. 1c). In most parts of north China including the CLP, a decreasing trend of the SP over the last 50 years is positively correlated with weakening of the monsoonal wind intensity defined as a dynamical normalized wind seasonality index (Li and Zeng, 2002). In south China, particularly over the middle and lower reaches of the Yangtze River, however, summer precipitation increases gradually over the last 50 years due to the southward shift of the monsoonal rain belt, and is negatively correlated with weakening of the monsoonal wind intensity. An anti-phase response of regional summer precipitation change to insolation forcing between north and south China was also identified in the transient simulations (Shi et al., 2012; Liu et al., 2014). A continuous simulation of the East Asian monsoon (EAM) revealed that from the LGM to Holocene maximum, an enhanced southerly monsoon wind is accompanied by an increased monsoon rainfall in north China, but not significant rainfall changes in southeastern China, implying that the precipitation change in north China is positively related to the monsoon intensity (Liu et al., 2014).

From a paleomonsoon perspective, it's difficult to infer the summer monsoonal wind intensity from geological archives. Most understanding of summer monsoon intensity is based on the precipitation-related proxies derived from pedogenic intensity of Chinese loess and isotopic composition of speleothems, although the extent to which these proxies can be interpreted as a pure summer monsoon indicator is still debated (Wang et al., 2001, 2008b; Cheng et al., 2009, 2012; Clemens et al., 2010; Dayem et al., 2010; Pausata et al., 2011; Maher and Thompson, 2012). Recently, comparison of observation data and isotope modeling results suggests that the strong summer monsoon can be characterized by intensified southerly wind, corresponding well to negative $\delta^{18}O$ over China and enhanced rainfall in northern China (Liu et al., 2014). Therefore, the paleo-precipitation change in northern China, including loess-based precipitation proxies on the CLP, most likely reflects the summer monsoon variation.

3. Material and methods

Two loess sequences at Jingyuan (JY, 36°20′30″N, 104°37′24″E) and Gulang (GL, 37°28′43″N, 102.52′28″E) are located in the northwestern CLP, close to the northern limit of the summer monsoon front (Fig. 1a). SP at these two sites contributes to 75% of the annual precipitation over the past 50 years, with ~60% water vapor transported by the southerly monsoonal wind (Yan et al., 2013). High sedimentation rate and weakly weathered loess sequences at the northwestern CLP can resolve millennial through glacial–interglacial monsoon variability (Sun et al., 2010, 2012b). Samples at 10-cm intervals were collected from the upper 110 m of two profiles including two 20-m loess pits in the uppermost part for measurements of magnetic susceptibility (χ), grain size and carbon isotopes of inorganic carbonates ($\delta^{13}C_{IC}$). Grain size distribution was determined using a Malvern 2000 laser instrument after removal of organic matter and carbonate. Magnetic susceptibility was measured with a Bartington MS 2 m. Carbon and Oxygen isotopes of inorganic carbonate of loess samples were measured using an isotope ratio mass spectrometer (MAT-252) with an automated carbonate preparation device (Kiel II). Standard deviation of carbon isotopic results is smaller than ±0.1‰ estimated from repeated analyses of the laboratory standards.

The response of monsoon circulation to insolation and glacial forcing is not consistent in different models, particularly the