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Precession and glacial-cycle controls of monsoon precipitation isotope changes over East Asia during the Pleistocene

Enqing Huang [a,*], Yunru Chen [a], Enno Schefuß [b], Stephan Steinke [b,c], Jingjing Liu [a], Jun Tian [a], Gema Martínez-Méndez [b], Mahyar Mohtadi [b]

[a] State Key Laboratory of Marine Geology, Tongji University, 1239 Siping Road, 200092 Shanghai, China
[b] MARUM – Center for Marine Environmental Sciences, University of Bremen, 28359 Bremen, Germany
[c] Department of Geological Oceanography and State Key Laboratory of Marine Environmental Science, Xiamen University, Xiamen, China

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ABSTRACT

Precipitation isotope reconstructions derived from speleothems and plant waxes are important archives for understanding hydroclimate dynamics. Their climatic significance in East Asia, however, remains controversial. Here we present terrestrial plant-wax stable hydrogen isotope (δD_{wax}) records over periods covering the last four interglacials and glacial terminations from sediment cores recovered from the northern South China Sea (SCS) as an archive of regionally-integrated precipitation isotope changes in Southeast China. Combined with previous precipitation isotope reconstructions from China, we find that the SCS δD_{wax} and Southwest-Central China stalagmite $\delta^{18}O$ records show relatively enriched and depleted isotopic values, respectively, during interglacial peaks; but relatively similar isotopic variations during most sub-interglacials and glacial periods over the past 430 thousand years. During interglacial peaks, strong summer insolation should have intensified the convection intensity, the isotopic fractionation along moisture trajectories and the seasonality, which are all in favor of causing isotopically-depleted rainfall over the East Asian monsoon regime. These effects in combination with a relatively high proportion of Indian Ocean- versus Pacific-sourced moisture influx should have resulted in strongly depleted precipitation isotopes (stalagmite $\delta^{18}O$) over most parts of China. However, Southeast China should have been affected by a relatively low ratio of Indian Ocean- versus Pacific-sourced moisture influx, which dominated over effects yielding depleted precipitation isotopes and led to enriched precipitation isotopes (δD_{wax}). It is thus concluded that glacial boundary conditions and insolation forcing are the two most important factors for causing regional differences in precipitation isotope compositions over subtropical East Asia on orbital timescales.

1. Introduction

Over the past two decades, speleothem-derived climate reconstructions have been put forward as benchmarks for tropical hydroclimate in the late Quaternary. Among all speleothem records from global tropical–subtropical regions, Chinese stalagmite records receive the most attention due to their precise chronologies, high temporal resolutions and long stratigraphical range (e.g., Wang et al., 2008; Cheng et al., 2009; 2016). However, the climatic interpretation of Chinese stalagmite $\delta^{18}O$ records remains enigmatic and is still under debate (e.g., Clemens et al., 2010; Liu et al., 2014; Tan, 2014).

One interpretation of the stalagmite $\delta^{18}O$ variations suggests that they represent changing summer monsoon rainfall amounts at cave locations (e.g., Wang et al., 2008). This, however, is challenged by increasing evidence. First, in regional observational data, a large portion of variability in precipitation isotope composition at inter-annual timescale cannot be explained by the 'amount effect' (Rao et al., 2016). Second, summer rainfall in Central and South China strongly depends on the position and northward migration of the rain belt known as the Meiyu Front, which results in a partly decoupling of summer monsoon rainfall from monsoon wind intensity and precipitation isotope composition (Ding et al., 2008; Liu et al., 2014). Third, the annual precipitation over China is derived from multiple sources, which deliver moisture with distinct isotope compositions at different seasons. For instance, precipitation around the Yangtze River (Central China, Fig. 1) originates from three major sources, the Indian Ocean, the western Pacific (including the South China Sea, SCS, and the East China Sea) and

* Corresponding author.
E-mail address: ehuang@tongji.edu.cn (E. Huang).

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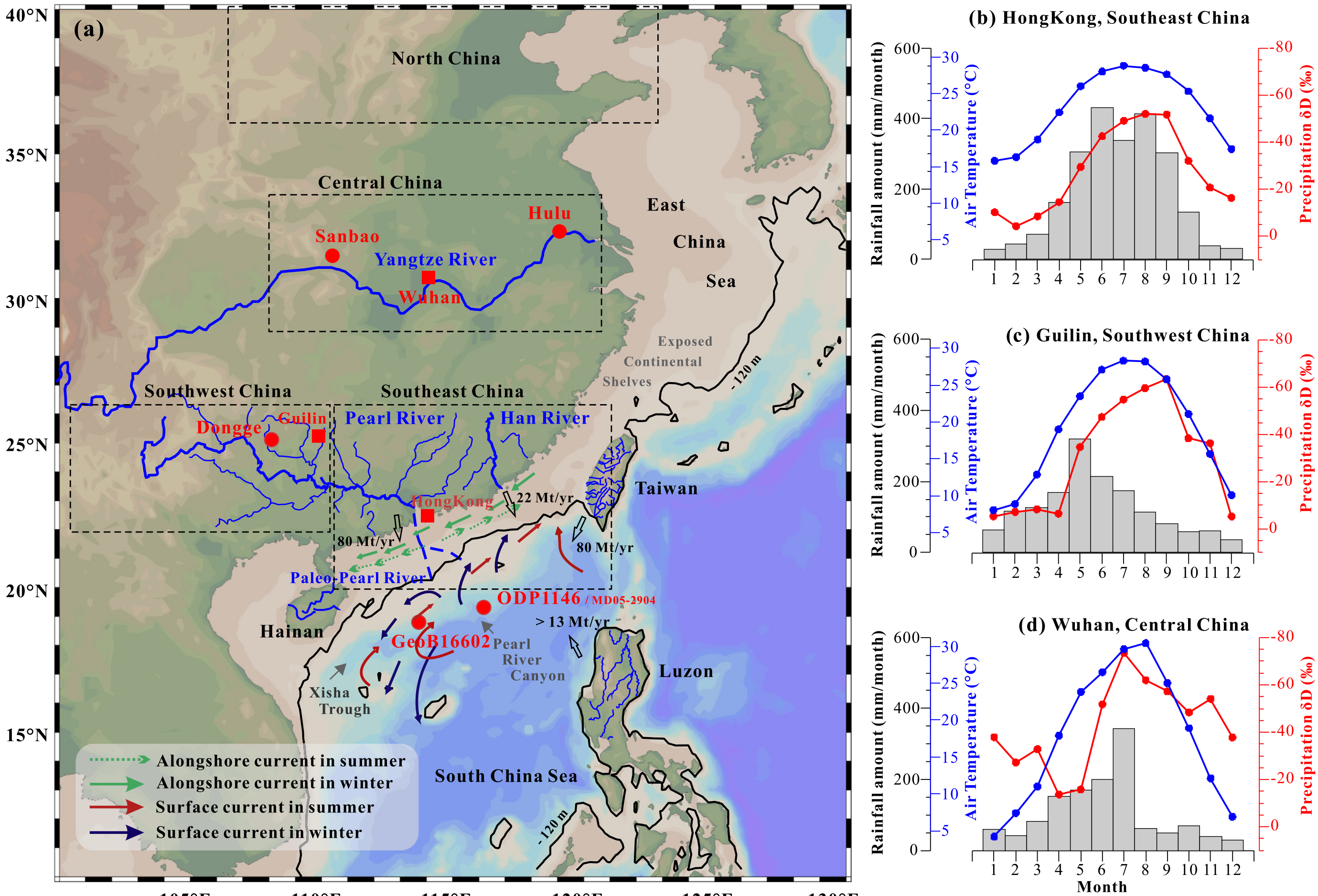

Fig. 1. Regional climatology and geographic locations of marine sediment cores, cave speleothems (red dots) and meteorological stations (red squares). (a) Modern (blue solid lines) and paleo-river (blue dashed lines) systems around the northeastern SCS, ocean currents (dark blue, red and green lines with arrows), −120 m isobath (solid black line) and the exposed continental shelves during the Last Glacial Maximum are indicated. Surface currents are modified from Fang et al. (1998). Hollow arrows indicate the annual-mean sediment discharge rate of each river system (Milliman and Farnsworth, 2011). Monthly-mean rainfall (grey bars), air temperatures (blue curves) and precipitation δD values (red curves) of Hong Kong, Guilin and Wuhan are plotted in (b), (c) and (d), respectively (International Atomic Energy Agency, 2013). (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

the northern high-latitudes that have been inferred to account for 16%, 23% and 42% of the total precipitation, respectively, during summer monsoon season (May–September) and 13%, 28% and 48% during wintertime (October–April, Sun and Wang, 2015). Although the proportion of moisture from different sources remains similar between the two seasons, the precipitation isotopic composition during summertime is much more depleted than during wintertime (Fig. 1d). This is mainly caused by strengthened convection over source regions and distillation along transport paths that both result in isotopically-depleted precipitation over Central–South China during summer monsoon seasons (Cai et al., 2017). Therefore, some studies interpret the Chinese cave $\delta^{18}O$ records as the ratio between summer and winter rainfall (e.g., Cheng et al., 2009). Isotope-enabled model simulations also corroborate the importance of upstream isotopic fractionation, especially during summer, on Chinese cave $\delta^{18}O$ signals (Pausata et al., 2011; Battisti et al., 2014; Liu et al., 2014).

Between the two oceanic moisture sources, Pacific-sourced moisture is generally more isotopically enriched relative to the Indian Ocean-sourced moisture because of the short air-mass trajectory and the weak rainout effect (Maher and Thompson, 2012). Therefore, other studies suggest that past changes in the ratio of Pacific- to Indian Ocean-sourced moisture reaching mainland China could also alter the isotope signature in precipitation (e.g., Maher and Thompson, 2012; Tan, 2014). This inference has been confirmed by a high correlation between the El Niño-Southern Oscillation (ENSO) index and Central–South China precipitation $\delta^{18}O$ changes at inter-annual timescale (Tan, 2014; Cai et al., 2017), suggesting that a more complete understanding of precipitation $\delta^{18}O$ fluctuations must invoke the Pacific surface thermal evolution in the past. Indeed, transient climate simulations imply that precession-modulated changes in intensity and position of trade winds as well as the Western Pacific Subtropical High could have a strong impact on Pacific-sourced moisture flux into China (Caley et al., 2014; Liu et al., 2014).

With respect to Central China, South China receives more moisture from the two oceanic sources with seasonal changes. The western Pacific and the Indian Oceans are estimated to be responsible for 30% and 35% of the total precipitation during the summer monsoon season, and 51% and 25% during wintertime, respectively; while terrestrial-sourced moisture only contributes 17% of the rainfall during both seasons (Sun and Wang, 2015). Within South China, the eastern region was inferred to be influenced by a higher ratio of Pacific- relative to Indian Ocean-sourced moisture than the western part during summertime (Tan, 2014; Cai et al., 2017). This is evidenced by the frequent occurrence of relatively heavy precipitation $\delta^{18}O$ values ($>-4‰$) in South Taiwan, Hong Kong, Haikou and Guangzhou during the summer monsoon season (Fig. S1a and S1d; International Atomic Energy Agency, 2013). Therefore, Southeast China, particularly the coastal regions,