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Heterodynes dominate precipitation isotopes in the East Asian monsoon region, reflecting interaction of multiple climate factors

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A B S T R A C T

For the past decade, East Asian monsoon history has been interpreted in the context of an exceptionally well-dated, high-resolution composite record of speleothem oxygen isotopes ($\delta^{18}O_{cave}$) from the Yangtze River Valley. This record is characterized by a unique spectral response, with variance concentrated predominantly within the precession band and an enigmatic lack of variance at the eccentricity and obliquity bands. Here we examine the spectral characteristics of all existing >250-kyr-long terrestrial water isotope records in Asia, including a new water isotope record using leaf wax hydrogen isotope ratios from the Chinese Loess Plateau. There exist profound differences in spectral characteristics among all orbital-scale Asian water isotope records. We demonstrate that these differences result from latitudinal gradients in the influence of the winter and summer monsoons, both of which impact climate and water isotopes throughout East Asia. Water isotope records therefore do not reflect precipitation during a single season or from a single circulation system. Rather, water isotope records in East Asia reflect the complex interplay of oceanic and continental moisture sources, operating at multiple Earth-orbital periods. These non-linear interactions are reflected in water isotope spectra by the presence of heterodynes. Although complex, we submit that water isotope records, when paired with rapidly developing isotope-enabled model simulations, will have the potential to elucidate mechanisms causing seasonal precipitation variability and moisture source variability in East Asia.

1. Introduction

1.1. Motivation

For the past decade, well-dated, high-resolution records of speleothem oxygen isotopes ($\delta^{18}O_{cave}$) from the Yangtze River Valley have been used as the basis for inferring East Asian monsoon history (Cheng et al., 2016, 2009; Wang et al., 2008). The composite of these records is characterized by a unique spectral response, with variance concentrated predominantly within the precession band, and an enigmatic lack of variance at the eccentricity and obliquity bands. Yet, orbital-scale records of East Asian monsoon strength not based on water isotope proxies contain spectral variance at all three of the primary orbital periods, suggesting that the monsoon is influenced by mechanisms operating at all three of the primary orbital bands (Clemens et al., 2010; Sun et al., 2015, 2010). Despite these differences between proxy records, the $\delta^{18}O_{cave}$ record has been interpreted to reflect summer rainfall as a direct function of East Asian summer monsoon circulation strength (Cheng et al., 2016, 2009; Wang et al., 2008). In turn, the summer monsoon has been interpreted to respond solely to the precession-band forcing of Northern Hemisphere summer insolation. Other research suggests, however, that precipitation isotopes ($\delta^{18}O$ and $\delta^{2}H$) in East Asia are more complex, and likely also reflect isotopic distillation along the pathway from the Indian Monsoon or other moisture source regions (Lee et al., 2012; LeGrande and Schmidt, 2009; Liu et al., 2014; Pausata et al., 2011), and/or a mix of precipitation isotope variability from multiple moisture sources and seasons (Baker et al., 2015; Caley et al., 2014; Clemens et al., 2010; Duan et al., 2016; Maher, 2008; Thomas et al., 2014a). This broad array of interpretations reflects the complexities of precipitation isotopes, which change as a func-

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tion of moisture source area, seasonality, temperature, and aridity, among other variables (Bradley et al., 2010; Duan et al., 2016; Orland et al., 2015; Thomas et al., 2016).

Multiple environmental variables operating at different seasons are not consistent with a simple spectral response dominated by precession, driven predominantly by northern hemisphere insolation forcing. Instead, such a system should be characterized by complex spectra, reflecting interaction among these multiple environmental variables (Clemens et al., 2010; Rial and Anaclerio, 2000). Understanding the influence of environmental variables on precipitation isotopes is key to our ability to effectively use precipitation isotope records as indicators of past climate change. Five >250-kyr-long water-isotope records exist for the Asian monsoon region (Fig. 1), all exhibiting profoundly different spectral responses (Cai et al., 2015; Kathayat et al., 2016; Thomas et al., 2014a; Wang et al., 2008). Each of these records has heterodyne-rich spectra, implying that multiple environmental forcing mechanisms influence each of these records.

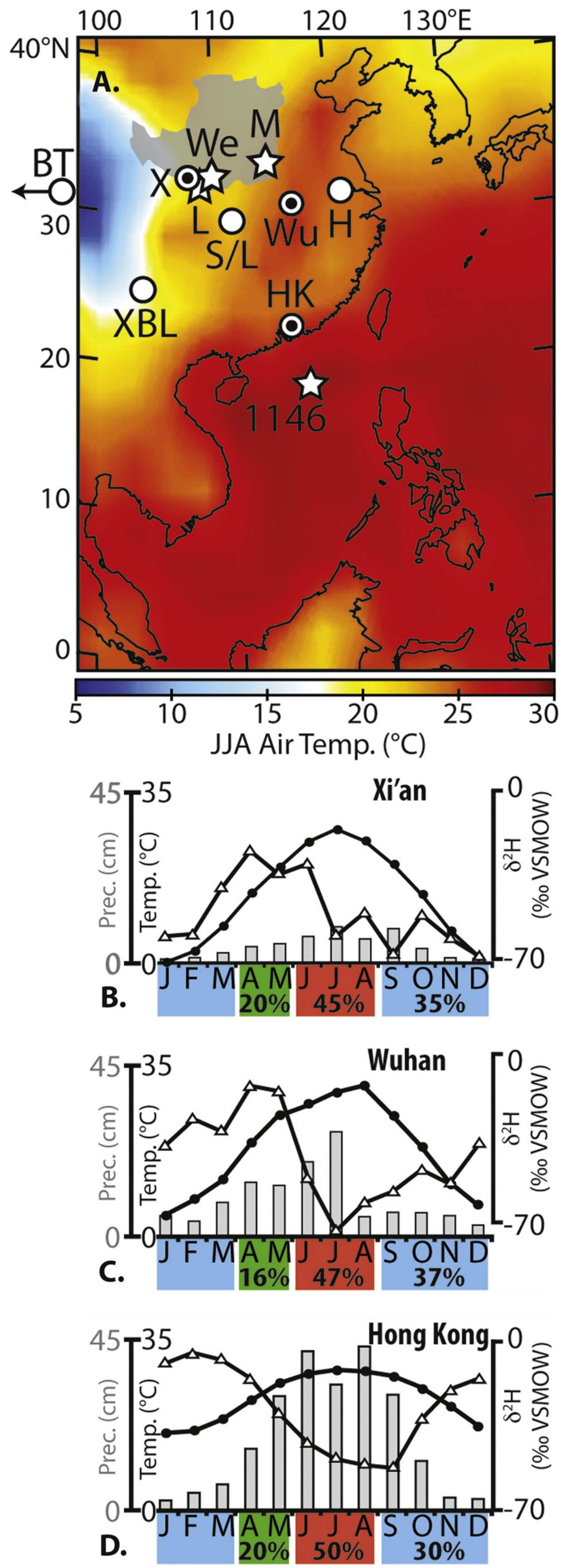

Fig. 1. Location of study sites and modern climatology. A. Map of East Asia showing study sites on the Chinese Loess Plateau (stars: L—Lantian, We—Weinan, M—Mangshan), the Yangtze River Valley and other cave sites (white dots: BT—Bittoo cave, XBL—Xiaobailong cave, S/L—Sanbao and Linzhu caves, H—Hulu cave), and the South China Sea (star: ODP Site 1146, which receives terrestrial material from the Pearl River catchment in southeastern China) (Thomas et al., 2014a). Location of modern meteorological stations shown with bullseyes (X—Xi'an, Wu—Wuhan, HK—Hong Kong). B.–D. Data from modern meteorological stations showing monthly mean precipitation (Prec., gray bars; seasonal percent of annual precipitation is at bottom), air temperature (black), and precipitation δ^2H (δ^2H_p, white) (IAEA/WMO, 2011). VSMOW—Vienna standard mean ocean water. B. Xi'an. C. Wuhan. D. Hong Kong.

1.2. Modern precipitation sources and seasonality

Modern gradients in temperature, precipitation seasonality and moisture source regions across East Asia cause gradients in precipitation isotopes (Fig. 1) (Baker et al., 2015; Clemens et al., 2010; IAEA/WMO, 2011; Johnson and Ingram, 2004; Sun and Wang, 2014). In the Pearl River Valley, southeastern China, precipitation is derived from the Bay of Bengal, the South China Sea, the western Pacific, and from locally recycled moisture (Sun and Wang, 2014). Precipitation isotopes in southeastern China are ^{2}H-enriched during the winter, when moisture is derived mainly from locally recycled sources, and is ^{2}H-depleted during the summer, when moisture is derived from far-traveled sources (Fig. 1D) (IAEA/WMO, 2011). In the Yangtze River Valley, central China, precipitation is derived from similar sources as in southeastern China, but with a greater contribution year-round from northwesterly and locally-recycled moisture sources (Sun and Wang, 2014). Precipitation isotopes in central China are most ^{2}H-enriched during the spring, when oceanic moisture is derived mainly from the East China Sea (Chiang et al., 2015; Clemens et al., 2010), and otherwise exhibit similar patterns as in southeastern China (Fig. 1C). On the Chinese Loess Plateau, northern China, precipitation is derived mainly from locally recycled moisture, but is also derived from the Bay of Bengal, the South China Sea, the western Pacific, and from northwesterly sources. Oceanic moisture sources are reduced during the winter. Precipitation isotopes in Xi'an, northern China exhibit similar patterns as in central China (Fig. 1B). Modern precipitation patterns suggest that the winter monsoon (continental moisture) exerts a greater influence in northern East Asia, whereas the summer monsoon influences all of East Asia (Baker et al., 2015; Sun and Wang, 2014). Precipitation moisture source and transport dynamics likely changed over geological time scales, influencing precipitation isotopes differently in each region (Baker et al., 2015; Chiang et al., 2015). Water isotope proxy records reflect changes in moisture sources and seasonality and can elucidate regional variations in mechanisms that influence precipitation isotopes.

1.3. Orbital-scale water isotope records

Orbital-scale terrestrial water isotope records in East Asia are derived from leaf wax hydrogen isotope ratios (δ^2H_{wax}) and speleothem carbonate oxygen isotope ratios ($\delta^{18}O_{cave}$). Existing