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An 8,600 year lacustrine record of summer monsoon variability from Yunnan, China

Aubrey L. Hillman [a, *], Mark B. Abbott [b], Matthew S. Finkenbinder [c], JunQing Yu [d]

[a] Department of Environmental Science, School of Geosciences, University of Louisiana at Lafayette, 611 McKinley St, Lafayette, LA 70504, USA
[b] Department of Geology and Environmental Science, University of Pittsburgh, 4107 O'Hara St, Pittsburgh, PA 15260, USA
[c] Department of Environmental Engineering and Earth Science, Wilkes University, 84 West South St, Wilkes-Barre, PA 18766, USA
[d] Qinghai Institute of Salt Lake Studies, Chinese Academy of Sciences, 18 Xinning Rd, Xining, Qinghai 810008, China

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ABSTRACT

Interactions between the Indian Summer Monsoon (ISM) and East Asian Summer Monsoon (EASM) are complex, yet needed to provide a long-term perspective of precipitation patterns in southeast Asia. Here we present an 8600-year sediment record from Xingyun Lake in Yunnan, China, a transitional zone that receives inputs of precipitation from both the ISM and EASM. Analysis of stable oxygen isotopes ($\delta^{18}O$) from authigenic calcite yields a semi-quantitative estimate of the timing and magnitude of lake level change that reflects changes in effective moisture from monsoon variability. Between 8600 and 6900 years BP, $\delta^{18}O$ values are stable and low, indicating high lake levels and overflowing conditions resulting from a strong ISM. After 6900 years BP, $\delta^{18}O$ values shift to higher values, which we suggest reflects a weakening of the ISM caused by declining summer insolation. The most substantial positive shift in isotopes occurs from 5000 to 4300 years BP and is coincident with aridity in India and the Tibetan Plateau. Other proxy records indicate increased ENSO variability and a southward shift in the ITCZ, which has an effect on the strength and onset of the ISM and may account for this change in hydrologic balance. After 4300 years BP, $\delta^{18}O$ values continue to increase reflecting a gradual drying trend, but increases are smaller than prior periods, in part due to lake bathymetry that limits the potential for isotopic enrichment driven by evaporation. The relative influence of the ISM and EASM in the Yunnan Province of China during the Holocene remains a topic for future study, but our results suggest the predominance of the ISM and a possible connection to ENSO patterns on centennial to millennial timescales.

1. Introduction

The Indian Summer Monsoon (ISM) provides water to over a billion people and comprises the western component of the larger Asian Summer Monsoon (ASM) system, which also includes the East Asian Summer Monsoon (EASM) (Fig. 1A). Regions affected by the ISM are not limited to the Indian sub-continent, but extend across Southeast Asia. People who live in these regions base their livelihood on the timely arrival of the ISM and precipitation to deliver enough water to sustain agriculture and hydroelectric power. Climate model simulations indicate the ISM will increase in strength, but become more variable in both timing and magnitude due to future climate change (Lal et al., 2011), which has important implications for agricultural production, water resource management, and hydropower generation.

Over longer timescales such as the Holocene, there is debate over how the ISM relates to the EASM. Some palynological studies from lakes in regions of China dominated by the ISM suggest the warmest and/or wettest conditions occurred during the early Holocene (Chen et al., 2014; Shen et al., 2006), in agreement with speleothem records interpreted in the context of the ISM (Fleitmann et al., 2007), whereas others find evidence for a wet middle Holocene (Song et al., 2012; Xiao et al., 2014), more in accordance with speleothem based proxy records of the EASM (Wang et al., 2001, 2005). On multi-to sub-decadal time scales, the relationship between the ISM and the EASM remains unclear, though modeling results suggest an asynchronous relationship (Li et al., 2014) as well as different responses to internal climate oscillations such as the El Niño Southern Oscillation (ENSO) (Wang et al., 2003). Understanding how the ISM interacts with the EASM

* Corresponding author.
E-mail address: aubrey.hillman@louisiana.edu (A.L. Hillman).

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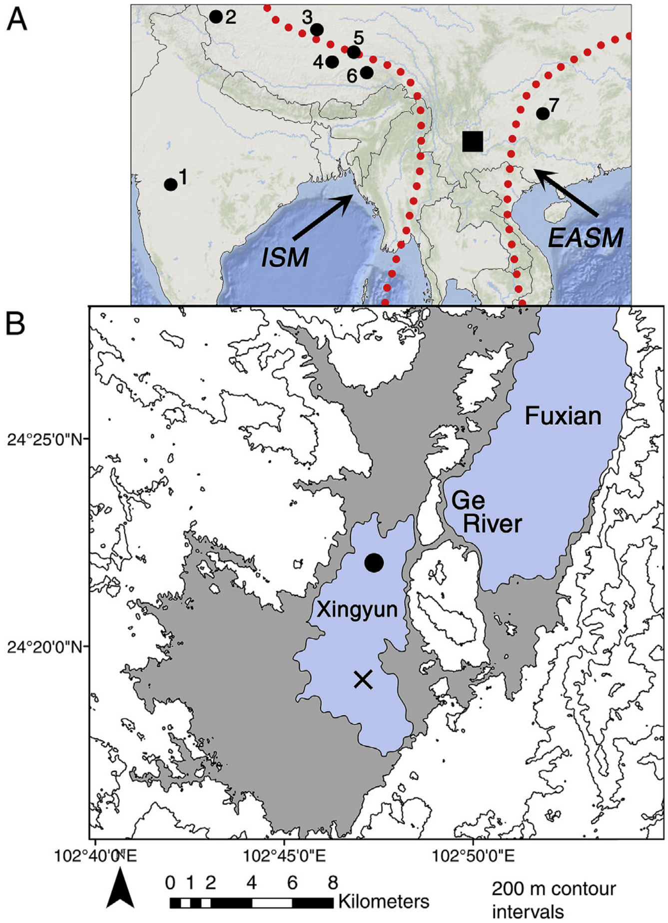

Fig. 1. A- Xingyun Lake (black square) with other paleoclimate archives discussed (1 = Lonar Lake, 2 = Bangong Co, 3 = Puruogangri Ice Core, 4 = Tianmen Cave, 5 = Ahung Co, 6 = Paru Co, 7 = Dongge Cave). Generalized boundaries of the Indian Summer Monsoon (ISM) and East Asian Summer Monsoon (EASM) are marked by the red dotted line. (B) Xingyun Lake (1721 m elevation), coring location marked by the black circle, and surrounding watershed with 200 m contour intervals. Deposits of Quaternary alluvium shaded in gray. Previous coring location of Hodell et al. (1999) marked by X. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

in the context of future, projected warming will be critical for regions that are affected by both monsoon systems, such as southern China. Therefore, a long-term perspective of the relationship between the ISM and EASM can provide information about the nature of rapid shifts in moisture balance in regions with essential water resources.

Despite the importance of the ISM as a critical water resource, there is a paucity of continuous terrestrial records of ISM precipitation over a wide enough spatial gradient to understand its variability and relationship with internal climate oscillations, such as ENSO (Turner and Annamalai, 2012). Many lake records from the Indian subcontinent are not continuous through the Holocene (Dixit et al., 2014; Prasad and Enzel, 2006), though Lonar Lake is an exception (Sarkar et al., 2015) (Fig. 1A). While many speleothem records sensitive to EASM variability have been produced from interior and coastal eastern China, speleothem records sensitive to ISM precipitation variability such as Tianmen (Cai et al., 2012) (Fig. 1A) and Mawmlah (Berkelhammer et al., 2012) do not continuously span the Holocene. Other speleothem records are temporally limited (Berkelhammer et al., 2010) or are located spatially distant from the main component of the ISM on the Arabian Peninsula (Burns et al., 2004; Fleitmann et al., 2003).

To improve our understanding of lake hydrologic balance associated with changes in the strength of the ISM, here we present an 8600-year sediment record from Xingyun Lake (Fig. 1B), on the Yunnan Plateau, a region that is dominated by the ISM but lies at the transition boundary between the ISM and the EASM (Fig. 1A). Based on modern-day precipitation isotope values, lake water isotopes from Xingyun demonstrate that it is evaporatively enriched and therefore sensitive to changes in the balance between precipitation and evaporation. We use measurements of the oxygen isotopic composition of authigenic calcite ($\delta^{18}O$) to understand lake level fluctuations that are ultimately controlled by changes in effective moisture (precipitation minus evaporation) and hydroclimate.

2. Background

2.1. Monsoonal climate

The regional climate on the Yunnan Plateau is classified as Subtropical Highland, characterized by short, cool dry winters, and long, warm and humid summers (Kottek et al., 2006). 75% of the average annual precipitation falls in the months of June–September associated with the ISM (Table 1), though Yunnan lies within the transition zone of the ISM and EASM domains (Li et al., 2014) (Fig. 1A **and** S1). Strict spatial boundaries between the ISM and the EASM are difficult to define (Cheng et al., 2012) though previous researchers have suggested 103°E as the dividing line on the basis of summer prevailing winds (Zhang, 1988). This dividing line is very close to our study site and it is likely that these monsoonal boundaries have changed longitudinally throughout the Holocene given the magnitude of insolation changes, though this remains undocumented and unquantified.

Monthly precipitation isotope data from the Kunming Global Network of Isotopes in Precipitation (GNIP) station over the period of 1986-2003 AD shows a moderately strong negative correlation ($R^2 = 0.37$, $p < 0.01$) between precipitation $\delta^{18}O$ and monthly precipitation amount (Fig. 2A), and a moderately weak negative correlation ($R^2 = 0.19$, $p = 0.02$) between precipitation $\delta^{18}O$ and monthly temperature (Fig. 2B). This suggests that $\delta^{18}O$ values of precipitation are predominantly controlled by the amount of precipitation arriving at Kunming in the summer monsoon season, rather than by seasonal changes in atmospheric temperature. This phenomenon known as the precipitation amount affect (Dansgaard, 1964) is likely controlled by several processes including rainout, distillation, and vertical convective activity (Vuille et al., 2005).

Over millennial timescales, the dominant control on the strength of the Northern Hemisphere monsoon is mid-latitude summer precessional forcing (Kutzbach, 1981). Over centennial and decadal time-scales, controls on abrupt changes in ISM strength are less clear and researchers have suggested connections to Northern Hemisphere temperatures (Cheng et al., 2012) and/or Pacific sea surface temperature (SST) gradients, but the relative importance of each of these factors is still debated. The impact of Pacific SSTs on ISM strength is manifested through changes in the phase and strength of ENSO. During an El Niño event, warm SSTs in the eastern Pacific cause the Walker circulation cell that drives atmospheric convection to shift eastward. The intertropical convergence zone (ITCZ) is pushed further southward and this causes a decrease in atmospheric convergence in the eastern Indian Ocean (Berry and Reeder, 2014), increased SSTs (Kumar et al., 1999), and a delayed onset of the monsoon (Prodhomme et al., 2014). This has the overall effect of weakening the ISM while the opposite set of conditions exist during a La Niña event. Tropical SSTs gradients along the equatorial Indian Ocean are also impactful and when the