



Decoupled early Holocene summer temperature and monsoon precipitation in southwest China

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ABSTRACT

Proxy-based reconstructions of Holocene temperature show that both the timing and magnitude of the thermal maximum varied substantially across different regions. Given the 'Holocene temperature conundrum', it is becoming increasingly important to reconstruct seasonal temperature variations. As a major component of the global monsoon system, the Indian summer monsoon (ISM) transports moisture and heat from the tropical oceans to higher latitudes and thus it has substantial socioeconomic implications for its regions of influences. We developed a well-dated, pollen-based summer temperature record (mean July; MJT) for the last 14,000 years from Xingyun Lake in southwest China, where the climate is dominated by the ISM. MJT decreased during the Younger Dryas, increased slowly to high values during 8000–5500 yr BP, and decreased thereafter. The MJT record differs from that inferred using carbonate oxygen isotopes ($\delta^{18}\text{O}$) from the same sediment core. The latter record reflects variations in monsoon precipitation, with highest precipitation during the early Holocene (11,000–6500 yr BP). We propose that summer temperature and precipitation in southwest China were decoupled during the early Holocene. Both MJT and monsoon precipitation decreased after the middle Holocene, tracking the trend in boreal summer insolation. We suggest that greater cloud cover, associated with high precipitation and generated by a strong summer monsoon, may have depressed early Holocene temperatures that would otherwise be driven by greater summer insolation. Melting ice sheets in high-latitude regions and high concentrations of atmospheric aerosols during the early Holocene may also have contributed, in part, to the relatively cool summer temperatures.

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1. Introduction

Using 73 globally distributed temperature records, Marcott et al. (2013) found that global annual temperature shows an early Holocene maximum, followed by a cooling trend through the middle to late Holocene which ended in the preindustrial era. This finding,

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however, disagrees with simulated global temperature variations that show a warming trend during the Holocene, mainly attributed to rising atmospheric greenhouse gas concentrations and retreating ice sheets (Liu et al., 2014). Liu et al. (2014) suggested that the cooling trend in the global stack is driven mainly by a bias towards summer temperature in the Northern Hemisphere, because temperature reconstructions are dominated by several alkenone-based sea-surface temperature records. These conflicting results, namely the so-called 'Holocene temperature conundrum', highlight the need to reassess the sensitivity of current climate models, and to pay more attention to possible seasonality effects in proxy reconstructions (Liu et al., 2014). Modeled simulations of Holocene

summer temperatures show that summers were cooler over regions directly influenced by the Laurentide ice sheet during the early Holocene, whereas for areas elsewhere in the Northern Hemisphere, summer temperatures were dominated by orbital insolation (Renssen et al., 2009). Proxy-based reconstructions of Holocene temperature, however, have shown that both the timing and magnitude of the thermal maximum differed substantially among regions (Shi et al., 1993; Kaufman et al., 2004; Renssen et al., 2009; Zhang et al., 2017a, 2017b). The lack of summer temperature reconstructions from low-latitude land regions makes it difficult to establish temporal patterns of Holocene summer temperature variations across the broader landscape and to determine the underlying forcing mechanisms of temperature change.

The Indian summer monsoon (ISM) is a major component of the global monsoon system and it is initiated by differential sensible heating of continental and oceanic regions (Webster et al., 1998). The ISM plays a crucial role in transporting moisture and heat from the tropical ocean to higher latitudes (Fleitmann et al., 2003; An et al., 2011; Govil and Naidu, 2011). Changes in the ISM have substantial socioeconomic implications for regions under its influence, through changes in water availability. Currently, ISM variability, especially extreme precipitation conditions, can cause severe droughts or floods which affect large numbers of people (Webster et al., 1998). In response to recent global warming, precipitation in the ISM region has decreased substantially during the past half-century (Sinha et al., 2015) which potentially poses severe threats to terrestrial ecosystems. In addition, it was suggested that an increase in anthropogenic aerosols has caused a decrease in monsoonal precipitation in Asia during recent decades (Menon et al., 2002; Yu et al., 2016). Given the increase in human activities since the late 20th century, it is possible that the decoupling of temperature and ISM precipitation during the past half century is not linked to natural variability. On long timescales, it was found that precipitation in East Asia lagged the last deglacial warming by several thousand years (Peterse et al., 2011, 2014), and the timing of the Holocene ISM onset appears different with the beginning of warming (e.g., He et al., 2017). During the Holocene, climate boundary conditions were similar to those of today. Therefore we sought to investigate the natural variability of precipitation and temperature during the Holocene in the ISM domains, and to explore their underlying forcing mechanisms, to improve our ability to predict regional and global climate changes.

Yunnan Province, in southwest China, is within the area of ISM influence. Many tectonic (fault) lakes are distributed across the Yunnan Plateau. Although a substantial amount of paleoenvironmental research has been conducted on these lakes, including vegetation and climate reconstructions (Sun et al., 1986; Hodell et al., 1999; Shen et al., 2006; An et al., 2011; Cook et al., 2013; Chen et al., 2014a; Xiao et al., 2014; Zhang et al., 2017a), the regional patterns of Holocene climate and vegetation changes in the region are still poorly understood. For example, some studies detected an early Holocene climatic optimum (Cook et al., 2013; Chen et al., 2014a), whereas others suggest a middle or even late Holocene climatic optimum (Xiao et al., 2014). These differences limit our understanding of the evolution of the ISM during the Holocene. In addition, the lack of unambiguous precipitation and temperature records with robust chronologies from the same site also limits our ability to address the questions of whether precipitation and temperature respond directly, on orbital time scales, to Northern Hemisphere summer insolation forcing, without a phase lag, or whether the climate response is delayed by internal feedback mechanisms (Overpeck et al., 1996; Kutzbach et al., 2008; Clemens et al., 2010; An et al., 2011).

We have conducted detailed investigations of past climate using

sediments from Xingyun Lake in Yunnan Province, southwest China (Chen et al., 2014a, 2014b; Hillman et al., 2014, 2017; Wu et al., 2015a, 2015b; Zhou et al., 2015). Because of possible hiatuses in our previously studied sediment cores (e.g., Chen et al., 2014a) we were unable to obtain continuous records that span the entire Holocene. In the present study, we compared records from a suite of cores, collected from different parts of the lake, to address the possible occurrence of a sedimentary hiatus in Xingyun Lake during the transition from the late glacial to the early Holocene. This enabled us to develop a composite record with robust age control, from multiple cores; then we used an analysis of fossil pollen assemblages to reconstruct past mean July temperature (MJT). Subsequently, we compared the temperature record with monsoonal precipitation records that were inferred from lacustrine carbonate oxygen isotope ($\delta^{18}\text{O}$) records to study their phase relationship and possible underlying forcing mechanisms.

2. Geographic setting

Xingyun Lake (24°17'20"N–24°23'05"N, 102°45'18"E–102°48'30"E) is a hydrologically closed, shallow ($z_{\text{max}} = 11$ m), eutrophic lake in central Yunnan Province, southwest China (Fig. 1A; Zhang et al., 2010). The lake surface lies at 1722 m above mean sea level (a.m.s.l.). The surface area is 34.7 km² and the catchment area is 386 km². Drainage into the basin is primarily via rainfall and runoff, including inflow from more than 14 rivers (Zhao and Zhao, 1988). The lake drained northwards via a narrow channel of the Gehe River into Fuxian Lake, and eventually into the Nanpan River system. Today, several dams on the Gehe River regulate the water flow. Xingyun Lake is a freshwater lake with conductivity of 344 $\mu\text{S}/\text{cm}$ and the pH ranges from 8.4 to 8.7 (Song et al., 1994).

The lake lies within the ISM region (Fig. 1B), which has a monsoon climate characterized by warm, wet summers and cold, dry winters. Mean annual precipitation is ~1000 mm, with almost 80% falling from May to September, determined by instrumental measurements at the Kunming station, ~80 km north of Xingyun Lake, during the interval 1986–2003 (Fig. 1C). The climate of the region is relatively cool from October to April (mean 9–17 °C), and warm from May to September (mean 18–20 °C). Monsoon circulation strongly affects the isotopic composition of precipitation in Kunming and other areas dominated by the ISM, with lower $\delta^{18}\text{O}$ values during summer (Wei and Lin, 1994; Li et al., 2015b, 2016). The annual weighted mean $\delta^{18}\text{O}$ of modern rainfall at Kunming was –9.86‰ VSMOW and the $\delta^{18}\text{O}$ value of a water sample taken from Xingyun Lake in 2009 was –4.3‰ VSMOW, suggesting substantial evaporative water loss from the lake (Hillman et al., 2014).

The natural vegetation in the Xingyun Lake catchment is semi-humid, evergreen, broadleaved forest and pine forest, belonging to the subtropical evergreen broadleaved forest zone of the Yunnan Plateau (Editorial Board of Yunnan Vegetation in China, 1987). Because of human disturbance, however, most of the modern vegetation in the catchment consists mainly of cultivated plants and pine forest, with remnant broadleaved forest or shrubs, predominantly *Cyclobalanopsis delavayi*, *Castanopsis delavayi*, *Lithocarpus dealbatus*, *Quercus variabilis*, *Quercus senescens*, *Alnus nepalensis* and *Rhododendron* spp. (Editorial Board of Yunnan Vegetation in China, 1987; Chen et al., 2014b). The catchment geology includes dolomite, sandstone and sandy shale (Song et al., 1994), and *terra rossa* (red soil) is widely distributed in the catchment. Currently, the lake catchment contains large areas of flat land used for rice cultivation. The basin has experienced dramatic increases in soil erosion since about 500 CE, caused by increased deforestation and agricultural activity (Hillman et al., 2014; Wu et al., 2015a).

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