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A 14 ka high-resolution $\delta^{18}O$ lake record reveals a paradigm shift for the process-based reconstruction of hydroclimate on the northern Tibetan Plateau

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ABSTRACT

The influence of the mid-latitude westerlies (MLW) competing with the Asian summer monsoons (ASM) over the Tibetan Plateau (TP) remains a matter of discussion on how and to which extent both atmospheric systems have been controlling hydro-climate during the Holocene. Depleted oxygen isotopes in lake deposits were commonly interpreted in terms of enhanced summer monsoon moisture supply, implying a migration of the ASM deep into the interior of the plateau during Holocene periods. In order to test this relationship we used a high resolution oxygen isotope record (mean 20 yr resolution) in combination with carbonates and mineral phases, titanium flux, grain size and ostracod abundances derived from a 6.84 m long sediment core in the endorheic Kuhai Lake basin, north-eastern TP. The results confirm 1) continuous positive co-variance between enriched $\delta^{18}O_{carb}$ and total carbonates during the last 14 ka, indicative of dominant seasonal influence on multi-decadal to centennial scale isotopic signatures in lake water and respective carbonate precipitation, 2) negative co-variance between allochthonous sediment flux and $\delta^{18}O_{carb}$ (and carbonates) attributed to relative increase of flux rates during non-summer seasons, 3) correspondence of lake level variations with carbonate mineral phases and the occurrence/disappearance of ostracod assemblages, and 4) inverse relationships between isotopic signatures in ASM-dominated and MLW-controlled lake records across the TP. Enriched $\delta^{18}O_{carb}$ in Kuhai Lake sediments was primarily a result of high evaporation during the summer seasons, while ASM-related rainfall amount did not play an important role, likely counterbalanced by isotopic signatures from different water sources. Conversely, depleted $\delta^{18}O_{carb}$ was mainly attributed to water supply during non-summer seasons of colder temperatures and generally light isotopic signatures from MLW-derived sources. This finding may lead to a paradigm shift in such way that depleted $\delta^{18}O$ in carbonates is primarily not the result from ASM-related rainfall as previously assumed. The reconstructed hydro-climatic history of Kuhai Lake indicates the dominance of westerly-derived climate during the Younger Dryas interval (12.8–11.5 ka) under very shallow pond-like conditions. Despite climate amelioration during the early Holocene (11.5–7.5 ka) hydrological conditions remained unstable with frequent alternations between dominance of summer and winter seasons. During the middle Holocene (7.5–5.5 ka) the lake experienced highest lake levels dominated by summer monsoon-related water supply, assigned to the Holocene hydro-climatic optimum. Frequent high-amplitude fluctuations afterwards (5.1–2.9 ka) refer to cooling/drying events under enhanced MLW influence accompanied by a strong lake level decline. The

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late Holocene (2.9 ka- Present) period experienced moderate isotopic variations and fluctuating lake levels in response to variable influence of summer- or winter-related hydro-climatic conditions.

This seesaw-like pattern with amplitudes of >10‰ in $\delta^{18}O_{carb}$ resembles fluctuations in cave records and variations between air and seawater (Dole effect). High correspondence with cooling events derived from North Atlantic drift ice and meltwater discharge indicate close ties to northern hemispheric climate transmitted by the MLW across the TP.

1. Introduction

The Asian monsoon system (winter and summer monsoon) interacts with the mid-latitude westerlies over large parts of China. Both are considered the most prominent atmospheric systems which control climate in China and adjacent regions of Asia (Wang et al., 2001; Hu et al., 2008; Liu et al., 2014, Fig. 1). An increasing number of speleothem $\delta^{18}O$ records along the trajectories of the ASM show a close relationship with changes in rainfall intensity (precipitation amount) in response to orbital- and millennial-scale variations of the northern hemisphere insolation, ice volume and associated northern high-latitude climate, and sea level changes (An et al., 2012; Cheng et al., 2016).

Several past and recent studies proposed a migration of the Asian summer monsoon deep into the interior of the plateau during the early and middle Holocene (Gasse et al., 1991, 1996; Yao et al., 1997; Hou et al., 2017; Qiang et al., 2017) followed by a general decline of summer monsoon strength after about 6 ka, in accordance with the northern hemisphere insolation trend (e.g., Wanner et al., 2008). Such millennial-scale relationships have been discussed in light of sedimentary sequences from terrestrial and marine records (An et al., 2012; Nagashima et al., 2013; Chen et al., 2015). Most of them using $\delta^{18}O$ and partly also carbonates from lakes among other proxies, were interpreted in terms of enhanced summer monsoon influence during this time span (e.g., Lister et al., 1991; Gu et al., 1993; Gasse et al., 1996; Wei and Gasse, 1999; Morrill et al., 2006; An et al., 2012), independent of regional different hydro-climatic conditions and almost in line with monsoon records derived from isotopic signals preserved in speleothems. Hence, depleted $\delta^{18}O$ signals in cave records as indicators for ASM strength were consequently transferred to other sites on the TP (Liu et al., 2007; Mischke et al., 2008; Zhang et al., 2011; An et al., 2012; Li et al., 2017).

Some records close to the boundary of summer monsoon impact (transitional zone) and along the north-eastern monsoon realm of China, mainly controlled by the East Asian summer monsoon (EASM), however, suggest a shift of maximum effective moisture supply from the early to the middle Holocene (e.g., An et al., 2000; Chen et al., 2008, 2015; Rao et al., 2016b), indicating a delayed response to insolation forcing (Zhang et al., 2017).

Many interpretations lack an in-depth discussion of implicit and interacting processes which are fundamental preconditions for the understanding of hydro-climatic variations over longer time scales, thus limiting a simple transfer of isotopic signals in cave records to other sites of the TP. Some researchers already noticed inconsistencies in the interpretation of stable oxygen isotopes in lake records and argued that perhaps not all depleted $\delta^{18}O$ values can be fully assigned to summer monsoon rainfall amount (Henderson et al., 2010; Qiang et al., 2017) when considering local to regional conditions.

Observational and modelling results on spatial distribution patterns of oxygen isotopes in modern precipitation ($\delta^{18}O_p$) in China combined with the detection of potential water vapour sources and related seasonal rainfall patterns (Dayem et al., 2010; Yao et al., 2013; Yang and Yao, 2016; Li and Garzione, 2017) already indicate regional differences under modern climate settings and also during the Holocene (Rao et al., 2016a). They highlight the importance of seasonality and type of precipitation that control this spatial pattern over the entire TP (Yao et al., 2013; Curio and Scherer, 2016; Li and Garzione, 2017). A closer relationship between modern $\delta^{18}O_p$ and annual temperature variations apart from summer monsoon-affected sites were reported for the arid/semi-arid regions of the TP and adjacent regions (Pang et al., 2011; Yao et al., 2013, Fig. 1A).

A comparison of $\delta^{18}O$ and $\delta^{13}C$ in lake records from different parts of the world (Horton et al., 2016) shows, that their interpretations cannot be simply transferred to all lake systems. However, the authors highlight the importance of hydrological balance effects in lake systems by evaporation-induced enrichment of isotopes in response to changes in the precipitation/evaporation ratio (P/E), as also discussed in detail by several other authors (Talbot, 1990; Fontes et al., 1996; Leng and Marshall, 2004). Although it is known that isotopic fractionation in lake water is a complex interplay between different processes (Leng and Marshall., 2004; Zhang et al., 2011), the timing and sources of precipitation, related temperature and geographical location in addition to P/E ratios are important factors (Zhang et al., 2011 and references therein) that might be still underestimated in respect to different regions on the TP.

So far, high resolution isotopic records from lake sediments covering the entire Holocene hydro-climatic history of the TP and adjacent regions are still very rare and do not discuss potential seasonality effects on isotopic signatures in lake carbonates as a response to changes in the timing and source of precipitation beside an overall evaporation background process within local to regional hydro-climatic settings. Hence, our aim was to test and possibly modify the influence of the interplay between the ASM and MLW on the northern part of the TP by comparing highly resolved proxy data and involved processes with other records from the larger region.

We selected the hydrologically closed Kuhai Lake on the north-eastern TP at the boundary of modern summer monsoon influence and MLW impact as an ideal location for detecting past climatic influence by both atmospheric systems. Recent hydro-climatic interpretations based on records from this lake provided different results in respect of timing and sediment sources, vegetation history and stable oxygen isotopes (Mischke et al., 2010; Wischnewski et al., 2011; Li et al., 2017) that encouraged us to reconcile climate impact by process-based studies. High-resolution stable oxygen isotopes from authigenic carbonates in combination with other selected sediment proxies are considered most important tracers for the detection of hydro-climatic regimes in the local catchment and adjacent regions during the past 14 ka.

2. Study site

Lake Kuhai, a closed saline lake (approx. 49 km^2 in area, maximum water depth of 22.3 m and ~13.6 psμ), located in the