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 $\delta^{18}O_{\text{carb}}$ 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 $\delta^{18}O_{\text{carb}}$ (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 $\delta^{18}O_{\text{carb}}$ 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 $\delta^{18}O_{\text{carb}}$ 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
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 δ\(^{18}\)O,\(_{\text{carb}}\) 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.

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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 δ\(^{18}\)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 δ\(^{18}\)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 δ\(^{18}\)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 δ\(^{18}\)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 (δ\(^{18}\)O\(_{\text{p}}\)) 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 Sonner, 2016; Li and Garzione, 2017). A closer relationship between modern δ\(^{18}\)O\(_{\text{p}}\) 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 δ\(^{18}\)O and δ\(^{13}\)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; Wischniewski 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 psu), located in the
Fig. 1. Major atmospheric systems, climate domains in China (A), Lake Kuhai site (B) and lake basin characteristics (C). Coloured arrows: AWM = Asian winter monsoon (dotted blue), ISM = Indian summer monsoon (red), EASM = East Asian summer monsoon (orange); major position of westerly jet in summer (blue) and winter (dotted blue); the modern boundary of summer monsoon influence (dotted black lines) derived and modified after Yao et al. (2013) and Chen et al. (2015). Numbers indicate selected locations within the monsoon domains (red dots), transitional zone (yellow dots) and westerly domain (blue dots). Squares mark locations mentioned in the text and in Fig. 9: A = Kuhai Lake; B = Hala Lake; C = Manas Lake; D = Sumsi Co; E = Bangong Co; F = Seling Co; G = Koucha Lake and H = Dongge Cave. Numbered sites are listed in Table S1 (suppl. information.). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
north-eastern part of the TP at 4132 m above sea level (Fig. 1) and surrounded by a non-glaciated catchment of 712 km² was selected for this study. The lake water is stratified during the spring and summer season with a thermocline at 7–9 m water depth. Surface water reaches temperatures of up to 15 °C during summers while water temperatures below the thermocline decreased to 2.5–0.8 °C. Bottom waters remained oxygenized. Several rivers enter the lake of which the majority is episodically active in summer (Fig. 1). The lake is frozen between December and March. Permafrost is widely distributed in the entire catchment, thus limiting groundwater discharge. The lake is surrounded by several paleo-shorelines, of which the highest one was found ca. 8–10 m above the present lake level (Mischke et al., 2010). A former outflow was neither reported nor detected during our intensive morphological studies.

Only 57% of the modern mean annual precipitation (Maduo station, 120 km further south: ~332 mm, period: 1976–2010, http://www.cma.gov.cn) falls during the major monsoon period between July and mid of September, while 43% is related to off-monsoon precipitation mainly as snowfall in early spring and late autumn. Annual mean evaporation of about 1000 mm exceeds the precipitation by about three times. Mean annual air temperature is ~3.3 °C with a maximum of ~14 °C in July. Low temperatures, close to or below zero °C, commonly occur between September and April in this region. Vegetation in this high altitude region consists of sparse grassland used as pasture by local residents.

3. Methods

3.1. Coring and surface sampling

Sediment coring in Kuhai Lake was performed by a UWITEC short coring device using 3 m long PVCliners and a UWITEC90 coring system in overlapping (1 m) drilling technique from a floating platform including a fixed ground plate with funnel that guarantees coring within the same borehole and a fixed position for unleashing the piston. In total, 6 sediment cores were obtained from various sites and water depth within the lake. Cores KH14 and KH17 were taken from the deepest part of the lake (20.6 m water depth) at the same site (Fig. 1B, Table S3, supplement). They were cut lengthwise and sampled at 1 cm-intervals for further analysis. Core KH14 (2.84 m length) and KH17 (2 m individual lengths) were spliced toward a composite core by visual inspection and high-resolution (1 cm) geochemical data (Fig. S1, supplement) with a final length of 6.84 m, free of any sediment gap. Further sampling and analyses also included overlapping parts to evaluate the accuracy of splicing but final results of proxies refer to the composite core KH17. In addition, 102 surface samples from the entire lake were collected by a grab or short coring device. Only the upper 2 cm of sediment was subject to measurements of modern spatial grain size distribution, geochemical compounds, minerals, stable isotopes and ostracod assemblages. Here we only report the spatial distribution pattern of stable oxygen isotopes (δ18O). Measurements of inflowing river water, ponds from the catchment, rain/snowfall events and lake water during the field seasons in 2014–2016 included vertical profiles of dissolved oxygen (DO), water temperature, pH, electric conductivity, total dissolved solids (TDS) and stable isotopes (δ18O, δD).

3.2. Dating

Three sets of radionuclide 210Pb/137Cs dating for the upper 20–25 cm sediment of cores KH13, KH15 and KH16 were performed at Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences (NIGLAS). As the upper 10 cm sediment composition in core KH17 was similar to the other cores, except the lack of an algae layer at 10–12 cm sediment depth, we applied the results from KH15 (nearest to KH17 site, Fig. 1B) for calculating the depth for zero BP (1950 AD) and inherent reservoir errors (RE) down-core. Radionuclide dating from cores KH14 and KH17 was not possible because the obtained material was extremely soft (highest water content of up to 80% in the upper 10 cm) resulting in too less material for multiple sediment analyses (KH14) or was just missing (KH17).

Thirty-two radionucler AMS ages for cores KH14/17 from plant remains and various organic fractions (bulk, alkali-soluble and insoluble fractions) on selected 1-cm sediment slices down-core were provided by Beta Analytics, U.S. Results are listed in Table S2 (supplement). All ages revealed a RE calculated on the base of 210Pb/137Cs results and linear regression between dated samples, resulting in a mean RE of 2495 years for core KH17. A regression up to the core top as commonly used in other age-depth models was avoided because it would imply that the upper sediments had the same sediment density (compaction coefficient) as down core, which was not the case. Hence, linear regression to zero cm depth would result in a reduction of the RE by about 130–140 years, not consistent with all radionuclide time series for the upper 10–15 cm of the cores and also not supported by sediment composition. In order to consider the extreme low compactions in all upper cores with a mean resolution of 7 yr cm⁻¹ based on 137Cs data (for the down-core part: mean 20 yr cm⁻¹), the 210Pb/137Cs age (1950 AD) at 10 cm sediment depth and the respective RE seem reasonable. Previous results on a sediment core from the same lake based on a combination of different organic fractions for AMS dating (Mischke et al., 2010) were based on a much lower mean RE and thus provided a chronology which differed from the KH17 record. The final chronology of core KH17 converted to calibrated ages was derived from the R algorithm in Bacon (Blauuw and Christen, 2011) and is reported in ka.

3.3. Stable isotopes (δ18O, δD, δ13C)

Water samples for the determination of stable isotopes (δ18O, δD) were analysed at the School of Geological and Engineering Sciences, Nanjing University and NIGLAS (Fig. 4).

Measurement of the δ18O values from bulk carbonate in the KH17 sediments was performed at the Leibniz Laboratory for Radiometric Dating and Stable Isotope Research, CAU Kiel. Carbonates identified by XRD analyses were used to adjust the reaction time of individual samples for isotopic determination. Possible allochthonous carbonates from the catchment remained on a very low level (<5%) as revealed for fluvial sediments and aeolian deposits in offshore regions of the lake and thus did not significantly affect the overall isotopic variations.

Based on semi-quantitative X-ray diffractometric (XRD) results from the core, several carbonate mineral phases could be identified: calcite, monohydralcalcite (MHC), high-magnesian calcite (≥4 mol% MgCO₃; HMC), dolomite (Dol) and aragonite (Ara). The former two minerals dominated the bulk samples, while aragonite only occurred occasionally in low amounts, except for the period between 570 and 410 cm depth (Fig. 5, unit 2: ca.11.5–8 ka). The reported δ18O values however, are based on bulk carbonate. All carbonate minerals reacted completely during the measurement procedure.

Bulk δ18O is reflected by mass balance of the δ18O value for each mineral phase and its percentage contribution to the total carbonate. However, as discussed for three scenarios below, on average, the measured bulk δ18O of KH17 does represent similar δ18O values to calcite. The oxygen isotope fractionation for precipitating calcite, aragonite and HMC is very similar, differing at
identical ambient temperature by less than 0.5‰ (Friedman and O’Neil, 1977; Jiménez-López et al., 2001). On average, these minerals represent 70.4 ± 18.9% of the carbonates in KH17, while dolomite and high-magnesian calcite occupy the remaining part.

Compared to calcite at identical ambient temperature, the oxygen isotope fractionation for precipitating dolomite or HMC is higher by about 2.5‰ and 1.5‰, respectively (Jiménez-López et al., 2004; Vasconcelos et al., 2005).

Scenario 1): In the (unlikely) case where all minerals were precipitated contemporaneously, measured bulk δ18O would differ in KH17 by only about 0.5‰ (on average) from δ18O of calcite as calculated by mass balance.

Scenario 2): Assuming that dolomite and high-magnesian calcite were precipitated at higher ambient temperature but still from the same lake water as the other carbonates, the δ18O values of dolomite and HMC will be lower, and hence the difference from the other carbonates will decrease. At a 10°C higher temperature for dolomite precipitation, the δ18O value of dolomite will reach the same δ18O value as calcite. Overall, this scenario indicates that bulk δ18O would have similar δ18O values to calcite. On average, the difference will be <0.5‰, comparable with reported offsets for aragonite and Mg-calcite (Leng and Marshall, 2004) and dolomite (Morrill et al., 2006).

3.4. Carbonates

Total carbonates reported as CO2 and organic matter (OM) were retrieved by loss on ignition (LOI), following the procedures described by Heiri et al. (2001) and measured at Nanjing University. As the quantity of both components are influenced by grain size in bulk samples we corrected the results against the grain size fraction in KH17 by only about 0.5‰ (on average) from δ18O of calcite as calculated by mass balance.

Geochemical elements were identified by X-ray fluorescence (XRF) line scans on the second half of each KH17 core segment in 5 mm resolution using an Avaatech XRF core scanner at Yunnan Normal University, Kunming, China. Preliminary results were published by Hu et al. (in press). Here we refer to the results of titanium (Ti) as a representative of allochthonous flux.

3.5. Grain size

Grain size analysis in 1 cm resolution was performed at Nanjing University, using a Malvern Mastersizer 2000 analyser. Sample preparation included removal of carbonate and organic matter by 10% hydrochloric acid and 30% H2O2 according to ISO Norm 14688–1 (2011). Median grain size data was mainly used in this study for adjustment of the chronology.

3.6. Ostracods

Ostracods were collected from 968 samples (~3 g dry weight) following the procedures described by Mischke et al. (2003) and Yan et al. (2017), identified under a stereoscopic microscope and scanning electron microscope (SEM) at Department of Earth Science, Freie Universität Berlin, here reported in abundances [ln (sum+1)].

4. Results

4.1. Lithology and chronology

Sediment composition of core KH17 revealed laminated clayey-silty mud in most parts of the core. Variations in lamina thickness including distinct carbonate layers and non-laminated sequences in the lower part as reported by Mischke et al. (2010) also occurred in our core. Increased silty to sandy fractions were found between 240 and roughly 300 cm and from 526 cm down-core (Figs. 2 and 5). Carbonate-rich laminated mud and partly crumbly carbonates were found at 230–260 cm and at 420–526 cm core depth. Median grain size distribution confirms the majority of fine fractions between 10 and 20 μm in the upper 5 m of the core, while significantly coarser fractions up to 120 μm (median) dominated the lower part (Fig. 2A).

Our age model refers to radionuclide dating (Fig. 2B) and AMS radiocarbon ages (Fig. 2A) from different fractions. The uppermost dated samples in the core provided too old ages in comparison with calculated 210Pb/137Cs dating results at 10 cm sediment depth. Hence, AMS ages were affected by various processes (e.g., incorporation of old/dead carbon; limited exchange with atmospheric CO2) resulting in certain reservoir errors, not uniform within the entire lake, similar to Lake Qinghai (Henderson et al., 2010; An et al., 2012).

Those errors are very common in lacustrine sediments from the TP and adjacent regions, thus subject to discussions about potential reasons of contamination and their spatio-temporal differences in sediment records (Hou et al., 2012; Mischke et al., 2013). The RE in the core KH17 was calculated by interpolation between ages and the set age of zero BP at 10 cm core depth yielding a mean RE of 2495 years. Linear regressions of core sequences as used in a Qinghai Lake record (An et al., 2012) however, were not applied here because a continuous linear sedimentation rate was considered unlikely, according to grain size variations. Notably the ages in the lower part of the core (Fig. 2A) did not allow applying a linear regression due to expected much higher sedimentation rates of sandy sequences. Hence, those ages, consistent with increased sedimentation rates were applied, while the other ages were discarded from the age model (Fig. 2, Table S1). Both methods however, cannot fully resolve age uncertainties as the RE error might have been not constant over time. Hence, we consider our age model as the best approximation towards a reasonable chronology. A previously published age model from the lake (Mischke et al., 2010) revealed a rather different chronology mainly due to a much lower calculated RE. The reported age model for the last roughly 1000-yr sedimentation history reported by Li et al. (2017) was based on a RE close to our record and thus matches our chronology quite well.

4.2. Spatio-temporal distribution of selected proxies

4.2.1. Stable isotopes in modern surface sediments and water

Modern distribution of δ18O in surface samples of Lake Kuhai (ca. 15-yr average values) display a spatially heterogeneous pattern with values ranging between −9‰ and +2.5‰ (Fig. 3). Apparently, the distribution of lighter isotopic values is connected with inflowing rivers that transport isotopically light rain/snow and meltwater from surface soils into the basin, similar to reported assumptions from west Tibet lakes (Gasse et al., 1991, 1996).

Modern isotopic composition (δ18O, δD) of rain/snow, river and
Fig. 2. Chronology of core KH17 from the center of Kuhai Lake (a). $^{210}\text{Pb}/^{137}\text{Cs}$ age calculation from cores KH15 (b). Sediment succession in core KH14/17 for the upper 15 cm was almost identical to core KH15. The age zero BP (1950 AD) occurred at 9–10 cm sediment depth, according to $^{137}\text{Cs}$ peaks. Mean sedimentation rate by $^{210}\text{Pb}_{ex}$ according to the equation of Van Eaton et al. (2010) was calculated to 8.8 yr cm$^{-1}$, pointing to a difference of 27 years between $^{137}\text{Cs}$ and $^{210}\text{Pb}_{ex}$-calculation for the upper 10 cm sediment, probably due to a calculated mean sedimentation rate by $^{210}\text{Pb}_{ex}$ without considering very high water content in the upper 10 cm sediment and related compaction through depth.

Fig. 3. Spatial distribution patterns of $\delta^{18}\text{O}_{\text{carb}}$ in surface samples of Lake Kuhai (inverse distance weighted interpolation). Red stars mark the location of retrieved sediment cores with core numbers and mean $\delta^{18}\text{O}$ values at the core sites. Black dots indicate the location of surface samples. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
Fig. 4. Modern stable isotopes ($^{13}$O, $^{18}$D) from rain, snow, river and lake water of Kuhai and adjacent regions for different seasons. The local evaporative line (LEL) differs remarkably from the global meteoric water line (GMWL), due to evaporation effects. Off-monsoon and summer monsoon precipitation overlap, while lake water is significantly enriched by $>10\%$.

Fig. 5. Proxy records from Lake Kuhai KH17 core, lithology and calibrated $^{14}$C ages, plotted against sediment depth. Relative abundances of ostracods; median grain size variations in core KH17; determined mineral phases by XRD, comprising calcite (green), aragonite (Ara, pink), monohydrocalcite (MHC, blue) and high-Mg calcite/dolomite (HMC/Dol, brown); total carbonate (additive log ratio) derived from loss on ignition; $^{18}$O isotope record (blue line) and $^{13}$C isotope record (green line) from carbonates. Dotted lines mark boundaries between units 1–6 according to variations in oxygen isotopes, carbonates and titanium. Mid-point ages refer to the Bacon age-depth model (Fig. 2). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
lake water in Kuhai and adjacent regions (Fig. 4, Weynell et al., 2016) displays strong seasonal differences with generally lightest values during the colder seasons and significant enrichment of δ¹⁸O_rain accompanied by high deruterium excess between May and June (June-early July) and Oct./Nov. (Ren et al., 2013). Rainfall events during early July 2016 in the neighbouring Donggi Cona Lake (onset of summer monsoon) revealed heavy δ¹⁸O_p between 0‰ and −5‰ (Fig. 4), similar to observations in the distant Maduo County (Ren et al., 2013). Rain/snowfall at Kuhai Lake in early June 2015 revealed very light values between −10‰ and −12‰. Lake water however, was already isotopically enriched by about 8–10‰ in June/July (Fig. 4). This is comparable with 15-yr averaged δ¹⁸O_carb in surface samples. Occasional summer monsoon-related rainfall events with isotopically light values however, may have also contributed to the overall isotopic composition in Kuhai Lake but were counterbalanced by mixing processes in the lake and high evaporation during the summer period.

4.2.2. Proxies in core KH17: stable isotopes (δ¹⁸O, δ¹³C)

The sedimentary record of core KH17 (Fig. 5) is divided into 6 units based on major changes in mineral composition, carbonates, oxygen isotopes and titanium through depth. δ¹⁸O_carb ranges between 3.59‰ and −8.83‰ (mean: 2.67‰ for the units 2–6, of the entire Holocene) with lightest values in unit 1, interrupted by significantly heavier peaks in the middle part of this unit. During unit 2 δ¹³C_carb increases rapidly towards heavier values but displays frequent short-term fluctuations of about 4–5‰ during early and late parts of this unit. In comparison with the previous unit 2 fluctuations in unit 3 remain less pronounced with a mean of about −1.8‰ between stronger excursions (light values) at the beginning and the end of this unit. Frequent fluctuations with amplitudes of about 10‰ in δ¹⁸O_carb are recorded in unit 4. Variations throughout units 5 and 6 remain less pronounced compared to the preceding period and fluctuate around the modern mean value of −0.96‰ by about 3–5‰. Stronger excursions (lighter values) occurred at the beginning of unit 6. Carbon isotopes (δ¹³C_carb, Fig. 5) vary between 4.19‰ and −6.44‰ (mean: 0.1‰) and only partly follow δ¹⁸O_carb variations. Lightest values occurred in the middle part of unit 1 and in unit 4. Stronger fluctuations with a general increasing trend (heavier values) are recorded in unit 2, followed by relatively stabilized heavier values in unit 3 and a general declining trend thereafter peaking in unit 4. Units 5 and 6 are characterized by low-amplitude fluctuations with a slight increasing trend until the top of the core. Co-variation between δ¹³C_carb and δ¹⁸O_carb is insignificant for the entire Holocene record, even for individual chrono-sequences except for the Late-glacial period (Table 1, Figs. 5 and 6). This relationship is remarkably different from other closed lake systems, where both isotopes commonly co-vari (Talbot, 1990; Fontes et al., 1996; Li and Ku, 1997; Leng and Marshall, 2004; Horton et al., 2016), although the general trends of δ¹³C_carb follow those of δ¹⁸O_carb (Fig. 7). The overall weak correlation within the closed lake at site KH17 except for the lower part of the core (13.5–11.6 ka, Table 1) remains an unsolved phenomenon, although not a singularity compared to other lakes (e.g., Talbot, 1990; Horton et al., 2016). Hence, this aspect was excluded from further discussion.

4.2.3. Mineral phases and total carbonate

X-ray diffraction analyses (XRD) from KH17 sediments revealed different carbonate mineral phases that contributed to the total amount of carbonate (Fig. 5). Stoichiometric calcite occurred with relatively constant amounts of −10‰ throughout the record. MHC was present from unit 3 up-core with highest values of up to 15‰ in unit 3, with generally lower and fluctuating amounts (0–5‰) in units 4–6. This highly unstable mineral readily converts to calcite or aragonite in presence of Mg (Winland, 1969; Fukushima et al., 2011; Rodriguez-Blanco et al., 2014), while perhaps colder and deeper water conditions and potentially fast sedimentation rate are able to preserve this mineral (Hull and Turnbull, 1973; Li et al., 2008). MHC was found as a precursor or intermediate product during calcite formation (Fukushima et al., 2011). Surface samples from the entire Lake Kuhai revealed the majority of MHC in greater water depth below the thermocline.

The metastable aragonite, commonly indicating increased salinity of evaporative shallow marine water bodies in presence of Mg (Burton and Walter, 1987) also forms in supersaturated warm and shallow waters of lacustrine systems (Gasse et al., 1991; Roesser et al., 2016). Aragonite was mainly formed during unit 2 exceeding 20% of all identified minerals and occurred only sporadically afterwards. High-Mg calcite (>4 mole % Mg) and dolomite experienced several strong peaks in unit 4 (up to 50%). Slightly elevated amounts were also found in unit 6 (−15%). In modern sediments of Lake Kuhai, these minerals only occurred at few locations in shallow water environments above the thermocline, likely in association with microbial mediated processes as reported from Qinghai Lake (Deng et al., 2010).

Low carbonate content in core KH17 (here reported as CO₃, Fig. 5) was observed in units 1, 5 and 6 (mean: 6.5% CO₃). After a rapid increase in unit 2 with peak values of −45% CO₃ in the second half on this unit, a general decreasing trend in unit 3 and extreme fluctuations thereafter in unit 4 are recorded. Slight fluctuations in units 5 and 6 remain on a relatively low level (2–9%, mean: −6% CO₃). Carbonate generally co-varies with δ¹⁸O_carb (Table 1).

4.2.4. Grain size composition

Highly variable median grain size composition (Fig. 5) with dominance of coarsest fractions (sand: 80–120 μm) occurred in unit 1 and the early part of unit 2. Stronger fluctuations between coarse and fine fractions occurred simultaneously with heavier δ¹⁸O_carb, slightly higher carbonate and depleted δ¹³C in the middle part of this unit. During the succeeding units median values of 10–20 μm remained the dominant fractions with slightly coarser components in units 4 (middle part) and 6 (early part).

4.2.5. Allochthonous sediments (titanium)

Titanium is considered a representative component for

<table>
<thead>
<tr>
<th>Time period (ka BP)</th>
<th>Correlation (r)</th>
<th>δ¹³C_carb</th>
<th>δ¹⁸O_carb</th>
<th>δ¹⁸O_carb/Ti</th>
<th>Carbonate/Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–13.6</td>
<td>0.04</td>
<td>0.52</td>
<td>−0.56</td>
<td>−0.69</td>
<td></td>
</tr>
<tr>
<td>0–2.9</td>
<td>0.36</td>
<td>0.64</td>
<td>−0.65</td>
<td>−0.59</td>
<td></td>
</tr>
<tr>
<td>2.9–5.1</td>
<td>−0.18</td>
<td>0.92</td>
<td>−0.72</td>
<td>−0.72</td>
<td></td>
</tr>
<tr>
<td>5.1–7.5</td>
<td>0.11</td>
<td>0.80</td>
<td>−0.75</td>
<td>−0.67</td>
<td></td>
</tr>
<tr>
<td>7.5–11.5</td>
<td>0.09</td>
<td>0.70</td>
<td>−0.60</td>
<td>−0.49</td>
<td></td>
</tr>
<tr>
<td>11.5–13.6</td>
<td>0.80</td>
<td>0.53</td>
<td>−0.40</td>
<td>−0.37</td>
<td></td>
</tr>
</tbody>
</table>
Fig. 6. Chrono-sequences of KH17 record for δ¹⁸Ocarb (blue), carbonate (red) and titanium (black) with respective correlation factors. A: 13.6–7.5 ka. The shaded area marks a period of weak correlation between δ¹⁸Ocarb and carbonate/Ti. Important negative spikes of δ¹⁸Ocarb are assigned to periods of possible prolonged cold seasons. B: 7.6–5.1 ka; C: 5.1–2.9 ka; D: 2.9 ka – Present. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
allochthonous sediment supply to the lake. Relatively high and constant proportions occurred during unit 1, interrupted by stronger fluctuations in the middle part of this unit, contemporaneous with fluctuations in grain size, δ¹⁸O, δ¹³C and carbonate. Similar to the aforementioned proxies, Ti experienced strong fluctuations from low to high amounts in units 2 and 4, less pronounced in unit 3 and relatively stabilized higher input during units 5 and 6. Ti is negatively correlated with δ¹⁸O_carb and carbonate through all units and chrono-sequences (Fig. 5, Table 1).

4.2.6. Ostracods

Relative abundances of ostracods in Lake Kuhai referred to three species, *Limnocythere inopinata* (Baird, 1843), *Eucypris mareotica* (Fischer, 1855) and *Ilyocypris* sp., of which the latter one only occurred in few samples (Yan, 2017). *Leucocythere* sp. found together with *E. mareotica* in the lower part of a sediment core from the same lake as well as occasional occurrences of *Cyprideis torosa*, *Fabaeformiscandona danielopoli* and *Tonnacypris edlundi* (Mischke et al., 2010) were not recorded in KH17 core. According to Fig. 5,

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**Fig. 7.** Comparison of Kuhai KH17 isotope records (δ¹⁸O_carb, δ¹³C_carb, including 10-point running average) with the composite speleothem record from Dongge cave (Cheng et al., 2016), Dole effect (Severinghaus et al., 2009) with ages of excursions, North Atlantic hematite-stained grains (HSG, Bond et al., 2001), Insolation at 40° N (Berger and Loutre, 1991) and reconstructed lake level variations during the last 14 ka. Shaded grey areas mark HSG maxima; light blue areas and dotted line in the lake level record are estimated variations. Arrows show opposite trends between cave records and lake records (Kuhai Lake) in the westerly-dominated domains of the semi-arid/arid regions on the TP. YD: Younger Dryas; DACP: Dark Ages Cold Period; MCA: Medieval Climate Anomaly; LIA: Little Ice Age. [For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.]
ostracods occurred in high abundances in units 2, 4 and 6 but only occasionally or were completely absent in the other units 1, 3 and 5. Under modern conditions those ostracods only occurred in Lake Kuhai above 10–12 m water depth, of which *L. inopinata* is known as a typical shallow water species (Meisch, 2000; Mischke et al., 2008). Also *E. mareotica* was not found below 12 m water depth in surface samples of Kuhai Lake, although it is known that this species can live in greater water depth as reported from other Tibetan lakes (e.g., Mischke et al., 2003, 2008; Yan and Wünnemann, 2014). The reason for spatially limited presence of ostracods remains unclear but may be related to locally unfavourable living conditions in the lake, especially in the profundal zone.

5. Discussion

The high-resolution isotopic record from the Kuhai Lake at the transitional domain of summer monsoon influence may serve as a paradigm for the interpretation of regional hydro-climatic conditions in response to the interplay between westerly-derived climate and summer monsoon impact during the last 14 ka. In contrast to large-sized closed lake systems such as Qinghai Lake, for example, which generally provide subdued signals homogenized by the buffering of the large lake volume (Leng and Marshall, 2004), smaller endorheic (hydrologically closed) lakes like Kuhai are able to better reflect past variations in water balance and related isotopic effects preserved in lake carbonates. Even relatively short-term intervals are detectable if the temporal resolution of a record is high enough.

5.1. Hydro-climatic processes controlling δ18O

Complex isotopic fractionation processes in water bodies were discussed in a larger number of publications (e.g., Talbot, 1990; Fontes et al., 1996; Li and Ku, 1997; Leng and Marshall, 2004; Horton et al., 2016; Qiang et al., 2017). They all highlight the importance of evaporative enrichment in water bodies as a ratio of precipitation over evaporation (P/E). The isotopic composition of lake carbonates which typically precipitate in the upper water columns of a lake system however, reflect multiple processes related to temperature, disequilibrium effects (vital effects) and the initial isotopic composition of the water body (Leng and Marshall, 2004). The latter is influenced by local precipitation, river/groundwater discharge and — most important for the Kuhai record — the timing (season) of the source water supply. Isotopic composition of rain/snowfall however, depends on air temperature, moisture source and rainfall amount (Zhang et al., 2011).

Carbonate from the catchment transported by fluvial and aeolian processes revealed allochthonous carbonate content generally below 5% of dry bulk samples (dolomite: <1%) and suggest that almost all identified carbonate phases are of authigenic/endogenic/biogenic origin.

A strong evaporative enrichment of lake water by > 10‰ observed in many closed lake systems worldwide (Horton et al., 2016) also applies to Kuhai Lake, both in modern lake water and in lake carbonates of the past 14 ka. Similar to other lakes on the TP and adjacent regions (Morrill et al., 2006; Zhang et al., 2011; Qiang et al., 2017) temperature dependent equilibrium fractionation between water and calcite by a gradient of about –0.24‰/°C (Craig, 1965) is rather unlikely for the KH17 record and cannot explain the large variations solely.

In general, the preserved isotopic signals in lake carbonates reflect the averaged δ18O of lake water (δ18Owater) derived from the different proportions of year-round rainfall and related water supply. For the KH17 record the measured δ18Owater value in each sample provides a mixed signal of at least 20 years (mean) precipitation dependent on the overall P/E ratio. With respect to the summer monsoon domains in China Zhang et al. (2011) argued that the amount-weighted average isotopic composition of input water from precipitation masks seasonal differences between summer and winter precipitation which can be decoupled by considering the composition of δ18Owater against the ratios of summer to winter precipitation. This method however, is applicable for modern times with reference to instrumental precipitation data as done for many sites across the Tibetan Plateau (e.g., Yao et al., 2013; Ren et al., 2013; Li and Garijone 2017), but less applicable for past scenarios as reliable seasonal precipitation data is lacking.

Being aware of this aspect, we propose that the relation between authigenic/biogenic carbonates and their isotopic signal (δ18Owater) could be an appropriate measure for the detection of seasonal differences in source water supply under variable P/E conditions. Given the fact that authigenic (fine fraction) and biogenic carbonates preferably form in surface waters under warmer water temperatures, lower pCO2 and in response to photosynthesis of macroscopic plants and algae (Talbot, 1990; Fontes et al., 1996; Leng and Marshall, 2004), they reflect hydrodynamic conditions of the lake during summer, mainly associated with maximum phytoplankton productivity (Teranes and McKenzie, 2001; Leng and Marshall, 2004). This fully applies to the Kuhai Lake and suggests that δ18O in those carbonates reflect the isotopic composition of the lake water during the warm season of summer monsoon impact. Hence, evaporative enrichment causes heavier δ18Owater leading to co-variance with carbonate amount, given that bi-carbonate and respective cations are sufficiently available. During the “winter season”, here denoted to the period between mid of September and April, low temperatures, photosynthetic activity and carbonate precipitation are significantly reduced. Concurrent with low air/water temperatures and reduced evaporation isotopically lighter rain/snowfall, snowmelt and thawing of frozen ground (He et al., 2016) during spring (April/June) promote the prevalence of lighter δ18O in lake water. Modern precipitation data reveal ca. 43% of annual rain/snowfall during these seasons. Hence, low amount of carbonate precipitation co-varies with light δ18Owater taking into account that non-summer rain/snowfall and related runoff in the northern parts of the TP and adjacent regions is isotopically depleted (Tian et al., 2001; Yao et al., 2013). This pattern differs from the summer monsoon affected domains on the TP.

Conversely, if amount-controlled isotopically light summer monsoon rainfall in this region would have exceeded the evaporation effect, the resulting lighter lake water during summers should show a negative correlation with carbonate amount, as indirectly inferred from Holocene isotopic records on ostracods in Qinghai Lake sediments (Lister et al., 1991; Liu et al., 2007; An et al., 2012) and Koucha Lake (Mischke et al., 2008). These relationships however, were subject to modification, if other sources than local rain/snowfall (glacier meltwater and/or groundwater inflow, for example) contributed to the overall water budget. Changes in lake level (water volume) are expected to accelerate or mute those relationships as assumed for the Holocene Sumxi Co lake record in western Tibet (Gasse et al., 1991).

5.2. Seasonal effects and westerly influence during the last 14 ka

Transferring the aforementioned relationships to the KH17 lake record (Fig. 6A–D), our data reveal high carbonate content that always co-varies with heavy δ18Owater over the entire 14 ka. Correlation factors for individual time sequences range between r = 0.53 (p < 0.01) and r = –0.92 (p < 0.01) (Table 1). Those significant correlations are evidence that carbonate precipitation always increased with isotopic enrichment through evaporation, which should be a common process. One exception from this covariance relation is during the late Holocene when heavy δ18Owater is accompanied by light δ18Owater, the latter however, not significantly correlated with carbonate amount (Table 1).
falls into the period between 11.0 and 10.9 ka where heavier δ¹⁸Ocarb was accompanied by low carbonate content, possibly due to the input of fine-grained carbonate-poor aeolian sediments. Light δ¹³C values never corresponded with high carbonate content which should have been the case if isotopically light rain (δ¹⁸Owater) related to the amount effect of summer monsoon dominated the δ¹⁸Owater as indirectly inferred from other records on the northern TP (Bangong Co: Gasse et al., 1996; Qinghai Lake:; Colman et al., 2007; An et al., 2012; Lake Genggahai: Qiang et al., 2017; Kuhai Lake: Li et al., 2017), at least for certain time intervals such as the early and middle Holocene, for example. This assumption does not exclude a possible influence of lighter summer precipitation (amount effect) in that region but it may have been masked by the overall high evaporation, persisting low P/E ratio and recycled water vapour. Several studies meanwhile demonstrate that modern light δ¹⁸O during the summer season is not the only contributor to the lake’s water budget but more likely a mixture of different rainfall sources with different isotopic signatures (Tian et al., 2001, 2007; Yao et al., 2013; Ren et al., 2013; Yang and Yao, 2016), and local convective rainfall events (Curio et al., 2015; Curio and Scherer, 2016). They obviously counterbalance potential amount-weighted summer monsoon rainfall in the semiarid/arid regions of the TP (Dykoski et al., 2007; An et al., 2012; Lake Genggahai: Qiang et al., 2017). Moreover, snowmelt and the decay of frozen surface soils in combination with periglacial processes such as soil washing is highly active in this high-elevated region during spring and delivers higher proportions of weathered fine clastic material along with runoff from snowmelt (He et al., 2016) to the basin. The isotopic composition of the frozen soil water and snow (light δ¹⁸O) is mainly that of non-monsoon precipitation. Overall sediment flux during the summer season including local sheet flooding processes after occasional heavy rainfall events seems to have been comparatively lower.

5.3. Chronology of hydro-climatic variations

Variations in the isotopic composition of the KH17 record through time are discussed in combination with selected proxy data that monitor hydrologic variations of the water budget within the uncertainty of our age model.

5.3.1. Younger Dryas (YD: 12.8–11.5 ka)

Most depleted δ¹³C values and low carbonate content (calcite) dominated the YD interval between 12.8 and 11.5 ka, interrupted by a series of enriched values between 12.5 and 12.0 ka (Fig. 6A). Frequent fluctuations in grain size from sand to silt-clay fractions, high allochthonous flux (Ti) and the sporadic occurrence of ostracod valves (mainly E. mareotica, few L. inopinata and Illyocypris sp., Fig. 5, unit 1) indicate very shallow pond-like conditions with variable fluvial and likely aeolian impact (Fig. 7). According to our interpretation model discussed above, the Kuhai region experienced prolonged colder climatic conditions (winter season) with limited water supply, both during summer and winter. Only short-term spells of enhanced evaporation (heavier δ¹³C) of a still shallow and perhaps slightly saline water body (occurrence of aragonite, Fig. 5, unit 1) is recorded within a roughly 500-yr intermediate period. These cold and mainly dry hydro-climatic conditions are well-known from numerous climate records in China and other parts of central Asia, generally attributed to weak or absent summer monsoon impact and dominance of westerly-derived climate. Thus, our argument that depleted δ¹³C in the KH17 record is mainly associated with colder climatic seasons and water supply from sources other than the summer monsoon is reasonable. Records from the modern summer monsoon domains show opposite (heavier) isotopic signals (Fig. 7) which were interpreted as weak or non-summer monsoon impact during this time interval. (e.g., Wang et al., 2001; Yuan et al., 2004; Dykoski et al., 2005; Liu et al., 2014), thus lacking amount-related summer monsoon rainfall.

5.3.2. Early Holocene (11.5–7.5 ka, Fig. 6A)

The onset of the early Holocene climate amelioration after 11.5 ka is documented by a rapid increase of δ¹³Ccarb towards heavier values, contemporaneous with the increase of carbonate precipitation (Fig. 6A). Increasing primary productivity as revealed by a series of enriched values, contemporaneous with the increase of carbonate precipitation (Table 1). Similar factors of r = −0.59 to r = −0.72 (both p < 0.001) apply to Ti/carb and indicate that increased allochthonous flux occurred earlier than the onset of the summer monsoon season when light δ¹³Ccarb and low carbonate were detected. This relationship can be expected because a larger amount of sediment transport through aeolian processes is related to the winter and spring seasons (e.g., Yan et al., 2017). Moreover, snowmelt and the decay of frozen surface soils in combination with periglacial processes such as soil washing is highly active in this high-elevated region during spring and delivers higher proportions of weathered fine clastic material along with runoff from snowmelt (He et al., 2016) to the basin. The isotopic composition of the frozen soil water and snow (light δ¹⁸O) is mainly that of non-monsoon precipitation. Overall sediment flux during the summer season including local sheet flooding processes after occasional heavy rainfall events seems to have been comparatively lower.
Strong fluctuations with negative spikes at around 11.3, 11.1, 10.8, 10.6 and 10.2 ka however, are indicative of rather unstable climate conditions, switching frequently between summer and winter dominance, while detrital flux followed these fluctuations. Summer-related precipitation was obviously not enough for a continuously rising lake level, comparable with results from the nearby Qinghai Lake (Li and Liu, 2014; Liu et al., 2015; Chen et al., 2016a). The occurrence of aragonite and high abundances of ostracods (Fig. 5, unit 2) during this period indicates an increased but still relatively shallow saline water body which was subject to intensified evaporation, preventing the lake from further rise (Fig. 7A). This is very similar to reported high salinity of the shallow Koucha Lake (Mischke et al., 2008). Aragonite and ostracods both indicate that the water body of Kuhai Lake did not dramatically change and remained at ca. 12–14 m below its present level. Interestingly, the spikes in the KH17 record almost match periods of weakened summer monsoon influence recorded in cave records (Fleitmann et al., 2003, 2008; Cheng et al., 2016) within dating uncertainties. The ca. 800-yr long period of heavier δ18Ocarb and high carbonate precipitation after ca. 10 ka indicates stabilized hydrological conditions with relatively high influence of the summer season rainfall and related evaporative enrichment of lake water isotopes. A general trend towards the lighter δ18Ocarb accompanied by increasing Ti flux culminating in a strong negative peak at ca. 9.1 ka may indicate a stepwise shift from summer-to winter-dominated hydro-climatic conditions. Three pronounced negative spikes, centring at 9.1, 8.2 and 7.6 ka between extreme positive peaks (δ18Ocarb >0‰) occurred thereafter. The first two are assigned to well-known climatic (cooling) anomalies triggered by meltwater pulses into the North Atlantic (Alley et al., 1997; Ellison et al., 2006; Fleitmann et al., 2008) that caused a slow-down of the Atlantic meridional overturning circulation (AMOC, McManus et al., 2004) and its hemispheric-scale signal transfer across the TP, most likely by the MLW. Recently, this climate signal was also described from the nearby Donggri Cona lake record (Saini et al., 2017) and suggests a significant delay and/or earlier withdrawal of the summer season, comparable to the previous periods of negative spikes. The subsequent turn to extreme positive δ18Ocarb values indicates an abrupt short-term recovery to summer-dominated evaporative influence for both periods. Andersen et al. (2017) ascribed similar successions from a central European lake record to a period of higher-than-average temperatures that immediately followed the 8.2 ka event in response to an enhanced resumption of the AMOC. We postulate that this could also be a case for the Kuhai region.

5.3.3. Middle Holocene (7.5–2.9 ka, Fig. 6B and C)

This relatively long middle Holocene period appears in the KH17 record as two significantly different isotopic sub-units, divided into an early and late stage. The early part of the middle Holocene between 7.5 and 5.4 ka was characterized by generally stable hydro-climatic conditions as inferred from slight variations in carbonate content and Ti flux (Fig. 6B). Mean δ18Ocarb of −1.91‰ was heavier than the overall Holocene mean (−2.67‰) but lighter than the modern mean (−0.96‰). The lack of ostracods, disappearance of aragonite and first appearance of MHC that could be retained under deeper cold water columns below a developed seasonal thermocline (Hull and Turnbull, 1973; Li et al., 2008), (Fig. 5, unit 3) suggest an increased lake level probably up to its maximum Holocene stage (−10 m above the present level), due to increased precipitation mainly during the summer season (Fig. 7A). The onset of summer stratification in the water body was very likely. This overall positive water balance where precipitation exceeds water loss through evaporation (P/E ratio >1), must have occurred at least during the rainy periods, apparently in summer time. Loss by overflow during this period can be excluded from the geomorphological perspective. Following this assumption we can attribute this period to the Holocene hydro-climatic optimum, similar in timing to records from Hala Lake (Wünnemann et al., 2012; Yan and Wünnemann, 2014), Genggahai Lake (Qiang et al., 2017), Gounghai Lake (Chen et al., 2015; Rao et al., 2016a,b); Koucha Lake (Mischke et al., 2008) and records in arid central Asia (ACA) used for discussion in respect to the general competing influence between the EASM and the MLW (Chen et al., 2008, 2016a,b; An et al., 2012).

At Linggo Lake in the central-northern TP however, higher lake levels derived from δD variability were mainly associated with increased moisture supply from westerly sources, implying less influence of summer monsoon in this region (Hou et al., 2017). Isotope values and co-varying carbonate content in the Kuhai record indicate that amount-related summer monsoon rainfall with strongly depleted δ18O was also not the main supplier but more likely a mix of different water sources with an overall isotopic composition closer to the middle Holocene mean isotopic value that contributed to a positive water balance. By contrast, depleted values for this period mainly contributed by higher δ18O values from the northern Tibetan Plateau (Hou et al., 2016a), indicate that the water body of Kuhai Lake did not dramatically change, while dominant hydro-climatic conditions. Three pronounced negative spikes, centring at 9.1, 8.2 and 7.6 ka between extreme positive peaks (δ18Ocarb >0‰) occurred thereafter. The first two are assigned to well-known climatic (cooling) anomalies triggered by meltwater pulses into the North Atlantic (Alley et al., 1997; Ellison et al., 2006; Fleitmann et al., 2008) that caused a slow-down of the Atlantic meridional overturning circulation (AMOC, McManus et al., 2004) and its hemispheric-scale signal transfer across the TP, most likely by the MLW. Recently, this climate signal was also described from the nearby Donggri Cona lake record (Saini et al., 2017) and suggests a significant delay and/or earlier withdrawal of the summer season, comparable to the previous periods of negative spikes. The subsequent turn to extreme positive δ18Ocarb values indicates an abrupt short-term recovery to summer-dominated evaporative influence for both periods. Andersen et al. (2017) ascribed similar successions from a central European lake record to a period of higher-than-average temperatures that immediately followed the 8.2 ka event in response to an enhanced resumption of the AMOC. We postulate that this could also be a case for the Kuhai region.

Three peaks of heavier δ18Ocarb at around 6.6 ka, 6.4 ka and between 6.0 and 5.8 ka exceed the mean value by about 1.9‰ and suggest intermediate lake level fluctuations in response to reduced water supply and more effective evaporation during the summer season. The influence of cold-season climate and related water supply remained on a low level and might have been masked by stronger summer signals.

The decline to significantly lighter isotope values and reduction in carbonate, accompanied by increased Ti flux after 5.5 ka (second sub-unit of the middle Holocene) leads to a period of pronounced hydro-climatic fluctuations which corroborate the climate of summer monsoon strength in nearly all Chinese cave records after 6 ka (e.g., Wang et al., 2005; Liu et al., 2014).

Large-amplitude fluctuations of >10‰ for δ18Ocarb between 5.0 and 2.9 ka, synchronous with carbonate changes (highest correlation) and in antiphase with Ti flux (Fig. 6C) indicate frequent alternations between winter- and summer-dominated seasons on a multi-decadal timescale. The re-occurrence of ostracods, alternating peaks of high-Mg calcite/dolomite, calcite and MHC, supplemented by slight increases in median grain size (Fig. 5, unit 4), indicate a strong fluctuating but declining trend in lake level, perhaps with short-term desiccation phases between 3.5 and 3 ka (Fig. 7A). Subaerial exposure of lake deposits that were subject to drying effects are indicated by the presence of crumbly carbonates for this period. Differently from early Holocene isotopic variations we suppose that summer monsoon-related water supply remained very weak or even temporarily absent to enable this strong evaporative enrichment of δ18Ocarb and contemporaneous lake level decline from its highest stage to a swampy and/or pond-like environment with periodically desiccated stages within a few centuries.

Conversely, the strong negative isotope values indicate periods with dominance of non-summer water supply that remained less affected by evaporation. Such dramatic fluctuations in isotopic composition became accelerated due to a successively declining lake level and water volume. The related residence time of lake water was shortened mainly during the summer season.

It has been suggested that this period of aridification over the entire TP (within the uncertainty of individual chronologies) (Gasse et al., 1991, 1996; Wei and Gasse, 1999; Hou et al., 2016), in India and South Asia (Staubwasser et al., 2003; Domske et al., 2009; Leipe et al., 2014; Dutt et al., 2018) and in the Chinese monsoon realm.
In summary, the shortening of ASM in 2008 (Dong et al., 2015) though offsets in timing remain enigmatic. Qinghai Lake (Henderson et al., 2010). modern summer monsoon in regions in China and the Kuhai Lake record at the boundary of the YD with the onset of Holocene climate warming and the development of a persistent summer level above the modern boundary for living conditions of ostracods that is significantly correlated with $\delta^{18}O$ thereafter between 1.5 and 1.0 ka, contemporaneous with effective moisture supply during both seasons, similar to the modern time. A declining temperature and heavier values) for the same period and for the last 2 ka denoted to a record from stabilized hydrologic conditions under mean temperatures similar to these of today. The disappearance of ostracods between ca. 2.9 and 1.5 ka, reduction/lack of aragonite and high-magnesian calcite but higher percentages of MHC (Fig. 5, units 5–6) indicate an increased lake level above the modern boundary for living conditions of ostracods in Kuhai Lake. Furthermore, the development of a persistent summer stratification and likely better preservation of MHC after ca. 2.9 ka, centred at around 2 ka (Fig. 7A). This higher lake level similar to that of the modern time corresponds to frequent low-amplitude fluctuations of $\delta^{18}O_{\text{carb}}$ pointing to an overall increased water supply during both seasons, similar to the modern time. A declining lake level thereafter between 1.5 and 1.0 ka, contemporaneous with the so-called Dark Ages Cold Period (DACP), is indicated by stronger excursions of $\delta^{18}O_{\text{carb}}$ (alternating light and heavy values), the reappearance of ostracods and increased percentages of high Mg calcite/dolomite. We assume a stronger impact of the westerly-derived cold season hydroclimate in excess of summer monsoon-related rainfall. Conversely, the succeeding period of the Medieval Climate Anomaly (MCA) appears to have been more balanced in terms of P/E and related seasonal effects. Reverse conditions during the Little Ice Age (LIA) is assumed by the variations in $\delta^{18}O_{\text{carb}}$ and carbonate content, similar to a record from Qinghai湖 (Henderson et al., 2010).

5.3.4. Late Holocene (ca. 2.9ka-present)

In comparison with the preceding period, smaller-scale fluctuations around a mean value of $-2.58\%$ ($\delta^{18}O_{\text{carb}}$) occurred during the late Holocene (Fig. 6D). Generally lower carbonate content (5–10%) though positively correlated with $\delta^{18}O_{\text{carb}}$ and still negatively correlated with $\delta^18O$ flux suggests a return to stabilized hydrologic conditions under mean temperatures similar to these of today. The disappearance of ostracods between ca. 2.9 and 1.5 ka, reduction/lack of aragonite and high-magnesian calcite but higher percentages of MHC (Fig. 5, units 5–6) indicate an increased lake level above the modern boundary for living conditions of ostracods in Kuhai Lake. Furthermore, the development of a persistent summer stratification and likely better preservation of MHC after ca. 2.9 ka, centred at around 2 ka (Fig. 7A). This higher lake level similar to that of the modern time corresponds to frequent low-amplitude fluctuations of $\delta^{18}O_{\text{carb}}$ pointing to an overall increased water supply during both seasons, similar to the modern time. A declining lake level thereafter between 1.5 and 1.0 ka, contemporaneous with the so-called Dark Ages Cold Period (DACP), is indicated by stronger excursions of $\delta^{18}O_{\text{carb}}$ (alternating light and heavy values), the reappearance of ostracods and increased percentages of high Mg calcite/dolomite. We assume a stronger impact of the westerly-derived cold season hydroclimate in excess of summer monsoon-related rainfall. Conversely, the succeeding period of the Medieval Climate Anomaly (MCA) appears to have been more balanced in terms of P/E and related seasonal effects. Reverse conditions during the Little Ice Age (LIA) is assumed by the variations in $\delta^{18}O_{\text{carb}}$ and carbonate content, similar to a record from Qinghai Lake (Henderson et al., 2010).

5.4. Spatio-temporal bi-partite patterns of climate control on the TP

The overall inverse isotopic trends between ASM-dominated regions in China and the Kuhai Lake record at the boundary of modern summer monsoon influence are demonstrated in Fig. 7B and E. The increasing trend of depleted $\delta^{18}O_{\text{carb}}$ in cave records after the YD with the onset of Holocene climate warming and strengthened ASM corroborates the decrease of $\delta^{18}O_{\text{carb}}$ (towards heavier values) for the same period and for the last 2 ka denoted to the so-called “2ka shift” of increased ASM relative to the declining trend of the northern Hemisphere insolation (Fig. 7D, Cheng et al., 2016). Reverse relationships are detectable for the middle-to-late Holocene after ca. 6 ka. They clearly show that amount-controlled rainfall leading to depleted $\delta^{18}O$ in speleothem and lake records in the monsoon realm of China (e.g., Zhang et al., 2011; Cheng et al., 2016) cannot be simply transferred to the Kuhai Lake as its hydrology and isotopic composition of the lake water from which carbonates precipitate was not primarily affected by precipitation amount but obviously by P/E ratio (dominance of evaporation), temperature and source water with strong links to the MLW. Despite the so-called “temperature effect” (Tian et al., 2008) in the arid regions of the TP, the timing and sources of water supply contributing to the net balance of Kuhai Lake seem to have been an equally important factor. We assume that during the winter season an active Asian winter monsoon (AWM) did not play a role in terms of effective moisture supply due to its generally dry-cold nature derived from the Siberian high pressure system (Domroes and Peng, 1988).

The results from Kuhai Lake indicate that the influence of the MLW was stronger during phases of depleted $\delta^{18}O_{\text{carb}}$ attributed to prolonged “winter seasons” including spring melt processes and the delay and/or earlier withdrawal of the summer season (ASM-related rainfall patterns). This scenario, for example, was discussed for shorter time sequences during the late middle Holocene form isotope records of Genggahai Lake (Qiang et al., 2017) and Linggo Lake (Hou et al., 2017), for the LIA in the Qinghai Lake area (Henderson et al., 2010; Yan et al., 2017), and recently observed (2018) by a roughly 14 days delay of Qinghai Lake ice melt.

The phases of depleted $\delta^{18}O_{\text{carb}}$ partly resemble periods of weakened ASM influence (Fig. 7D) and even more clearly the deviation of the $\delta^{18}O$ in air from seawater $\delta^{18}O$, as a reasonable measure of ASM strength, known as Dole effect (Severinghaus et al., 2009, Fig. 7F). This coincidence may support the validity of our chronology within uncertainties.

Furthermore, the isotopic peaks in the Kuhai lake record resemble almost all phases of increased North Atlantic drift ice (Fig. 7G) indicated by hematite-stained grains (HSC) which reflect cooling events during the last 11 ka (Bond et al., 2001). Hence, it is reasonable to assume that those climate signals were transmitted by the MLW across the TP and induced short-term climate deteriorations even at sites close to the modern boundary of ASM influence. Suppose that those seasonal shifts are tied with the competing influence of both the MLW and ASM, a prolongation of the colder season climate depended on the strength of the MLW and the shifting pathway across the TP in relation to the ASM influence (Schiemann et al., 2009; Nagashima et al., 2013; Chiang et al., 2015) during the entire Holocene.

Taking the spatial distribution of modern annual precipitation, temperature and $\delta^{18}O_p$ over the TP and summer monsoon controlled regions in China into account (Fig. 8), arid regions with generally low annual precipitation display co-variance between temperature change and $\delta^{18}O_p$ (Yao et al., 2013). This applies to locations across the central and northern part of the TP, which are considered to be dominated by westerly-derived climate (Yao et al., 2013; Maussion et al., 2014) including some sites along the modern summer monsoon boundary (transitional zone; Fig. 1). Hence, isotopic signatures during summer are significantly enriched due to generally low P/E ratio and inland recycling processes in comparison to summer monsoon-controlled sites (Lhasa, Guiyang, XiAn, for example, Fig. 8) and other regions in the monsoon realm. This implies that precipitation amount in summer does not play any role and if so for certain rainfall events they are readily counterbalanced by the overall rainfall sources as discussed above. This modern scenario can be applied to past periods of the Holocene by isotopic signatures in available lake records across the TP.
records from ASM amount-affected sites in the north-eastern and south-western domains of the TP (Qinghai Lake: An et al., 2012; Bangong Co: Wei and Gasse, 1999; Seling Co: Gu et al., 1993; Wei and Gasse, 1999, Fig. 9F). They display remarkable differences in their isotopic signatures during the last 14 ka. Despite certain differences among the records due to chronological constraints, lower data resolution and local hydrological conditions, the records from the northern part of the TP display comparable isotopic trends as discussed for Kuhai Lake. They indicate a plateau-wide dominance of P/E ratio, temperature effect and source water isotopic composition under a persistent influence of the MLW and its seasonal effects on the isotopic composition during the entire Holocene. Hence, the amount effect of ASM-related rainfall in those regions did not play a role or was even absent. An exception can be inferred from the Koucha Lake (marked as a dotted line in Fig. 9E; Mischke et al., 2008) where the isotopic signatures from ostracods during the early Holocene seem to have been stronger influenced by the amount effect of a strengthened ASM. The chronology for this time period however, remains questionable. Ramisch et al. (2016) reported evidence from Lake Heihai on the north-western TP that the ISM could not pass the Kunlun Mt. range because of its topographic barrier function. It is however, an open question whether summer monsoon derived effective moisture could penetrate far into the interior of the TP during the early-middle Holocene as inferred from the available records (Gasse et al., 1991; Rhodes et al., 1996; Hou et al., 2017) and from the Guliya ice core Thompson et al., 1997; Yao et al., 1997).

A persistent increase of effective moisture after ca. 6 ka inferred from a loess-paleosol sequence in the Xinjiang region of arid central Asia (ACA, Chen et al., 2016b) cannot be detected in the lake records on the northern TP (part of the ACA). The record from Kuhai Lake indicates a general decrease of water volume after its lake high stand during the middle Holocene despite intermediate fluctuations.

By contrast, isotopic signatures in available lake records from the summer monsoon domain follow the isotopic trends in cave records (Fig. 7E). According to the modern distribution patterns of precipitation, temperature and δ18O (Fig. 8) in summer monsoon-dominated regions it is reasonable to assume similar conditions during the entire Holocene in those regions. This also

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**Fig. 8.** Selected sites of modern temperature (red line), precipitation (blue bars) and δ18O (black line) according to GNIP and TNIP data (Yao et al., 2011), showing a clear discrimination between summer monsoon influenced and westerly affected regions over the Tibetan Plateau and monsoon China. Green dotted line marks the modern boundary of summer monsoon impact in accordance with the mean annual precipitation distribution over China. See also Fig. 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
Fig. 9. Comparison of isotope records from various lakes on the Tibetan Plateau. Westerly domain: Kuhai Lake (this study), Hala Lake (Yan and Wünnemann, 2014), Manas Lake (Rhodes et al., 1996), Sumxi Co (Gasse et al., 1991; Wei and Gasse, 1999); ASM influenced domains: Koucha Lake (Mischke et al., 2008), dotted line indicates unclear chronology; Qinghai Lake (An et al., 2012), Bangong Co (Gasse et al., 1996; Wei and Gasse, 1999), Seling Co (Gu et al., 1993; Wei and Gasse, 1999), all redrawn according to published individual chronologies and related uncertainties. Shaded areas mark unstable climatic conditions during the early Holocene and late middle Holocene.

Westerly dominated sites (evaporation, seasonal precipitation, temperature)  Summer monsoon influence (precipitation amount)
implies that amount-controlled precipitation at the respective sites prevailed during the summer season, if other factors such as changes in the P/E ratio and isotopically light meltwater input from adjacent glaciers remained insignificant.

The isotopic records based on ostracod assemblages in Qinghai Lake sediments (Fig. 9F; Lister et al., 1991; Liu et al., 2007; An et al., 2012) few hundred km north of Kuhai Lake and in Koucha Lake sediments south of Kuhai Lake (Mischke et al., 2008), differ from the Kuhai record and roughly follow the trends of the isotopic record from Dongge cave (Dykoski et al., 2005). This trend however, is only visible in Koucha Lake for the early Holocene period (Fig. 9E) based on the respective chronology. Ostracod shells however, preserve the isotopic signal of the ambient water within few days during moulting in spring or summer (Meisch, 2000), given that adult specimens were used for isotope analysis. Hence, isotopic composition of the host water during other seasons cannot be preserved as ostracods only live for short periods within the summer season. Despite this limitation respective results were always interpreted in terms of strong summer monsoon influence although interacting with the MLW (An et al., 2012). Conversely, Henderson et al. (2010) argued that depleted δ18O from authigenic carbonates in Qinghai Lake were more likely associated with winter moisture signals during the Little Ice Age rather than summer monsoon, thus challenging the interpretation of climate signals by stable oxygen isotopes (Zhang et al., 2011). Given that summer monsoon dominance in that region was valid, the modern bulging shape of monsoon moisture intrusion into small parts of the north-eastern TP (modern monsoon boundary, Fig. 1) would have existed during most periods of the Holocene, whilst the neighbouring sites (Kuhai Lake, Hala Lake, Koucha Lake after the early Holocene) remained excluded, according to the different influencing factors discussed above. The isotopic record from Koucha Lake (Fig. 9E) resembles the isotopic signatures of the Kuhai record quite well for the younger period after around 7.5 ka indicating similar hydro-climatic variations as noticed in the other records from the westerly domain on the TP.

The spatially inverse isotopic records from lake carbonates reveal a clear discrimination between westerly-controlled and ASM-dominated regions across the Tibetan Plateau, underpinning the bipartite nature of climate control on the TP. Our data indicate that the modern domains reported by Yao et al. (2013) most likely existed over the last 14 ka, even during periods of positive water balances. A penetration of the ASM deep into the interior of the semi-arid/arid regions of the TP therefore remains questionable. Interpretation of ASM impact based on the amount effect is not applicable for lake records from the northern part of the plateau.

6. Conclusion

The high-resolution oxygen isotope record from Kuhai Lake carbonates in the north-eastern part of the Tibetan Plateau (transitional domain) in combination with selected sediment proxies was used to identify hydrodynamic variations in response to the interplay between the ASM and MLW. Our results show that the covariance between δ18O and carbonate content is a potential tracer for deciphering seasonality influence of climate in a decadal-to-centennial-scale over the last 14 ka. Evaporative enrichment of δ18O during the summer season dominated the isotopic composition of lake water and carbonates, outweighing potential amount effects from ASM-related rainfall. Hence, the trends of isotopic signatures along the northern part of the TP were inversely correlated with cave and lake records from the ASM-affected sites. Depleted values could be assigned to cold winter season climate and related water supply, mainly associated with the MLW. The seesaw-like pattern of isotopic variations with amplitudes >10‰ indicate frequent alternations between seasonally different hydroclimatic conditions that were dominant for decades. Most of the negative spikes in the Kuhai record resemble cooling events in the North Atlantic realm likely transmitted by the MLW and their seasonal shifts across the TP. They also corresponded to periods of weakened ASM in the monsoon domains and suggest a prolongation of the colder winter season coupled with a delay and or earlier withdrawal of summer season hydro-climatic conditions.

Sediment influx caused by eolian and fluvial processes exceeded the contribution during the summer season due to strong influence of periglacial processes and spring water snowmelt processes in high altitudes of the TP. Lake level fluctuations promoted accelerated or muted isotopic signatures. Shallow pond-like conditions with fluvial impact existed during the Younger Dryas event, followed by increasing but still lower lake level during early Holocene under unstable climatic conditions. The Holocene hydro-climatic optimum with highest lake level occurred during the middle Holocene, followed by a strong decline afterwards due to climate deterioration towards cold and dry conditions. The late Holocene experienced medium fluctuations which accord to known climatic oscillations during the last 2 ka.

Author contributions

BW and DY designed the project, wrote the draft version of the manuscript, performed the age model and analysed minerals and ostracods; NA and FR performed stable isotope data measurement and supported interpretation; YZ, QS, PH supported sediment analyses (grain size, minerals), statistics and text writing.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.quascirev.2018.09.040.

B: Lake Kuhai with locations of cores (red circles with core numbers), surface samples (yellow dots), water samples (blue dots) and catchment boundary (red line). The orange triangle marks the core data published by Mischke et al. (2010).

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