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Quaternary ecological responses and impacts of the Indian Ocean Summer Monsoon at Nam Co, Southern Tibetan Plateau

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A B S T R A C T

The transition from the Last Glacial to the current Interglacial, the Holocene, represents an important period with climatic and environmental changes impacting ecosystems. In this study, we examined the interplay between the Indian Ocean Summer Monsoon (IOSM) and the Westerlies at lake Nam Co, southern Tibet to understand the climatic effects on the ecosystem. Different organic geochemical proxies (*n*-alkanes, glycerol dialkyl glycerol tetraethers, δD, $\delta^{13}C_{org}$, $\delta^{15}N$) are applied to reconstruct the environmental and hydrological changes on one of the longest available paleorecords at the Tibetan Plateau. Based on our paleohydrological δD proxies, the aquatic signal lags the terrestrial one due to specific ecological thresholds, which, in addition to climatic changes, can influence aquatic organisms. The aquatic organisms' response strongly depends on temperature and associated lake size, as well as pH and nutrient availability. Because the terrestrial vegetation reacts faster and more sensitively to changes in the monsoonal and climatic system, the δD of *n*-C_{29} and the reconstructed inflow water signal represent an appropriate IOSM proxy. In general, the interplay of the different air masses seems to be primarily controlled by solar insolation. In the Holocene, the high insolation generates a large land-ocean pressure gradient associated with strong monsoonal winds and the strongest IOSM. In the Last Glacial period, however, the weak insolation promoted the Westerlies, thereby increasing their influence at the Tibetan Plateau. Our results help to elucidate the variable IOSM, and they illustrate a remarkable shift in the lake system regarding pH, $\delta^{13}C_{org}$ and $\delta^{15}N$ from the Last Glacial to the Holocene interglacial period.

1. Introduction

The Asian monsoon is an important component of the modern climate system, and it interacts with other subsystems, such as the El Niño-Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO) (Gupta et al., 2003; Kumar et al., 2006). The main driver of the Asian monsoon is the thermally induced pressure gradient between land and ocean based on their different warming (Li and Yanai, 1996). Therefore, the Tibetan Plateau may act as an elevated heat source that can enhance the Asian monsoon (An et al., 2001; Wu et al., 2012). This area is mainly influenced by the Indian Ocean Summer Monsoon (IOSM), which delivers the majority of the precipitation in the summer months, and by the Westerlies in the winter months (Leber et al., 1995; IAEA/WMO, 2012). However, the extent of the IOSM has changed, and several proxies have been used to track the variability of monsoon winds and/or monsoonal precipitation in the past (cf. Wang et al., 2005; Morrill et al., 2003, 2006). Oxygen isotope records from caves and ice cores are usually used to record the precipitation and temperature signal, respectively (Thompson et al., 1997; Grootes et al., 1999; Petit et al., 1999; Sinha et al., 2005; Shakun et al., 2007). The planktonic foraminifera *Globigerina bulloides* are often applied to track monsoon winds (Overpeck et al., 1996; Kudrass et al., 2001; Gupta et al., 2003).

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Over the last decade, hydrogen isotopes (δD) of *n*-alkanes have increasingly been used as a paleohydrological proxy (cf. Sachse et al., 2012 and references therein). *n*-Alkanes can be attributed to either aquatic or terrestrial organisms and reflect, among other factors, the isotope signal of their source water in their δD signal. Aquatic *n*-alkanes, which in Tibetan lakes predominantly comprise less than 25 carbon atoms, mainly record the isotope signal of the lake water (Günther et al., 2013). In contrast, terrestrial *n*-alkanes, which predominantly comprise more than 27 carbon atoms in Tibetan ecosystems, mainly reflect the meteoric water (Günther et al., 2013). The isotope signal is modified by evaporation as well as by transpiration and biosynthetic fractionation (Sessions et al., 1999; Mügler et al., 2008). Lacustrine *n*-alkanes are persistent over geological timescales and, therefore, enable the reconstruction of both lake water and meteoric water in paleoclimate studies (Schimmelmann et al., 1999; Pedentchouk et al., 2006). Glycerol dialkyl glycerol tetraethers (GDGTs) are membrane lipids that are often applied to reconstruct air and water temperatures in lacustrine systems (e.g., Sinninghe Damsté et al., 2009; Blaga et al., 2010; Wang et al., 2012). Branched GDGTs (bGDGTs) are mainly produced by bacteria, and their degree of cyclization (CBT) is correlated with soil pH (Weijers et al., 2007) as well as lake water pH (Schoon et al., 2013; Günther et al., 2014). The methylation of bGDGTs is correlated with air temperature and (soil/water) pH (Peterse et al., 2012; Günther et al., 2014). Isoprenoid GDGTs (iGDGTs) of archaeal origin are used to estimate water temperatures based on the TEX_{86} proxy (Schouten et al., 2002; Günther et al., 2014). Moreover, bulk organic isotope records ($\delta^{13}C_{org}$, $\delta^{15}N$) are used to describe the state and development of the lake system. $\delta^{13}C_{org}$ is a proxy used to determine the contribution of aquatic and terrestrial organic matter sources (Meyers, 1994), and $\delta^{15}N$ serves as a proxy for autochthonous primary production and the nutrient availability in lakes (Kendall, 1998).

These proxies are used to reconstruct the IOSM's dynamics and its impact on lacustrine sediments of lake Nam Co, on the southern part of the Tibetan Plateau. Numerous lake studies at the Tibetan Plateau have focused on changes of the IOSM during the Holocene (e.g., Morrill et al., 2006; Mügler et al., 2010; Kasper et al., 2012; Doberschütz et al., 2013), but only a few have investigated the transition from the Pleistocene to the Holocene (partially in Morrill et al., 2003; Liu et al., 2007; Wünnemann et al., 2010; Yan and Wünnemann, 2014). The current investigation focuses on the transition from the Last Glacial Maximum (LGM) to the Early Holocene and is an extension of the already-published Nam Co data covering the Holocene (Mügler et al., 2010). We analyzed the interplay between the IOSM and Westerlies as well as the related climatological, ecological and hydrological changes, at Nam Co during this period.

2. Materials and methods

2.1. Study site

With a water area of approximately 1920 km^2, Nam Co (30°30′–30°56′ N; 90°16′–91°03′ E; 4722 m a.s.l.) is the second-largest saline lake on the Qinghai–Tibetan Plateau (Fig. 1). The total catchment area spans 10,610 km^2 (Guan et al., 1984). The mean relative humidity is 52.6% (for 2005–2006) (Li et al., 2007). The mean annual air temperature (MAAT) is 0 °C, with a minimum of −26.4 °C (in February 2005–2006) and a maximum of 20.6 °C (in July 2005–2006) (Keil et al., 2010). The mean annual precipitation is approximately 281 mm, with the majority of precipitation between June and October delivered by the IOSM (Hren et al., 2009). From January to May, Westerly winds influence the lake (Keil et al., 2010). Precipitation and rivers, primarily entering the lake in the southern part, are the most important water supplies. Rivers are recharged by precipitation and glacial melt water from the adjacent Nyainqentanglha Mountain. Nam Co has no outflow, and hence, its water balance is solely controlled by the water input and evaporation. The mean annual evaporation from the lake surface and catchment is 790 mm and 320 mm, respectively (Zhu and Meng, 2004). Evaporation exceeds precipitation, and Nam Co is characterized by a semi-arid climate (Feng et al., 2006). The maximum water depth is approximately 99 m (Daut et al., 2010). The lake water is characterized by a high pH (from 8 to 9.7, averaging at 9.21) and a salinity of 1.8 g/l (in the years 2006–2008) (Wang et al., 2009).

2.2. Sampling and sample preparation

The sediment core NC 08/01 (30° 44′ 14.71″ N; 90° 47′ 25.19″ E), with a total length of approximately 10.4 m, was recovered from a water depth of approximately 93 m using a piston corer (UWITEC, Mondsee, Austria). Opening and sampling of the core was carried out at the geoecological–sedimentological laboratory at the University of Jena, Germany. The sediment samples were freeze-dried and homogenized for further analysis.

2.3. Dating

In total, 24 bulk samples of the sediment core were used for AMS ^{14}C radiocarbon dating carried out at Beta Analytics, Miami, USA. Based on the dating of recent sediments, the reservoir effect accounts for 1420 years (Kasper et al., 2012; Doberschütz et al., 2013). The modern ^{14}C reservoir age correction was applied for the entire core NC 08/01. The sediment core was sampled in 1-cm slices at 5-cm intervals and, according to the sedimentation rate, was pooled for lipid biomarker analysis, resulting in a mean time resolution of approximately 100 years.

2.4. Analysis of lipid biomarker compounds

Depending on the organic carbon content, 2–9 g of sample was used for lipid extraction. Total lipids were extracted twice with a mixture of dichloromethane/methanol (9:1, v:v) at 100 °C and 138 bar for 15 min using an accelerated solvent extractor (ASE-200, DIONEX Corp., Sunnyvale, USA). Activated copper was added to remove elemental sulfur. Total lipid extracts were separated over an activated silica gel column into aliphatic, aromatic and polar fractions and were eluted with hexane, chloroform and methanol, respectively (Sachse et al., 2006).

2.4.1. GDGTs

Glycerol dialkyl glycerol tetraethers (GDGTs) were analyzed at the Royal Netherlands Institute for Sea Research (NIOZ), Texel, Netherlands. Aliquots of the polar fractions were added with a known amount of an internal C_{46} GDGT standard (Huguet et al., 2006), dried under N_2, re-dissolved in hexane/isopropanol (99:1, v:v) and filtered through a PTFE syringe filter (0.45-μm pore size, 4-mm diameter). Ten milliliters of each sample was measured using high-performance liquid chromatography/atmospheric pressure positive ion chemical ionization-mass spectrometry (HPLC/APCI-MS) on an Agilent (Palo Alto, CA) 1100 LC/MSD SL system according to Schouten et al. (2007). The $[M+H]^+$ ions of the individual GDGTs were measured with single ion monitoring (SIM). Peak areas were integrated following the method of Weijers et al. (2007). The cyclization (CBT) of branched tetraether was calculated to compute pH using equations (1)–(2) with eq. (2) representing the local calibration for lakes on the Tibetan Plateau (Günther et al., 2014). The simplified methylation (MBT′) of branched tetraethers was used to determine the mean air temperature (MAT) using equations