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Influence of the Indian monsoon and the subtropical jet on climate change on the Tibetan Plateau since the late Pleistocene

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ABSTRACT

Precipitation atop the Tibetan Plateau (TP) is delivered by the Indian summer monsoon, the Asian summer monsoon, and weather systems associated with the subtropical westerly jet. Variations in the relative importance of the monsoon systems and the westerly jet are hypothesized to have occurred at decadal, millennial and glacial-interglacial scales. However, paleoclimate observations based on explicit climate proxies are still scarce, limiting our understanding of the mechanisms of Holocene climate variability on the Tibetan Plateau (TP). Here we present three independently dated compound specific hydrogen isotope records of sedimentary leaf waxes from lakes on the TP, Bangong Co, Lake Qinghai and Linggo Co. The leaf wax δD records reflect isotopes in precipitation, and we combine these observations with existing isotopic and hydrological data to investigate variations in the influence of the summer monsoon and the westerly jet on the moisture budget of the TP since the Late Pleistocene. δD values of precipitation at all three lakes were relatively positive during the Late Pleistocene indicating a weakened summer monsoon. During the early and mid-Holocene, δD values of precipitation at the three lakes were relatively negative, suggesting the importance of summer monsoon. During the middle to late Holocene, δD values at Bangong Co and Lake Qinghai gradually increased with superimposed episodes of short term of δD variability. However, at Linggo Co in the northern TP, periods of more positive δD values of precipitation correspond to wetter intervals inferred from lake level high stands, and likely reflect variations in moisture associated with the westerly jet. Thus, the δD records at Linggo Co imply the lesser importance of summer monsoon moisture in the hydrologic budget of the northern TP. Collectively, the hydrogen isotope records at these three lakes document millennial and centennial scale variations in the strength of the summer monsoon systems and concurrent changes in the westerly jet. Furthermore, millennial-scale fluctuations in the δD records at the three lakes during the middle to late Holocene suggest episodes of reduced summer monsoonal moisture delivery to these regions, and correspond with intervals of cool sea surface temperatures in the North Atlantic.

1. Introduction

The Tibetan Plateau (TP) is the highest and largest plateau on Earth, and hosts a wide array of mountain glaciers that provide the primary freshwater source to more than one third of the world's population (Immerzeel et al., 2010). The retreat and advance of the TP glaciers were significantly affected by precipitation patterns (Yao et al., 2012) and temperature variations (Bolch et al., 2012; Jacob et al., 2012) in recent decades, and the potential vulnerability of this important freshwater source is understandably of concern to society. The extent to which climate patterns could shift in response to future climate change is therefore an important subject of study, and observations of past climate variability on the TP are critical to this effort. The climate of the TP is influenced by multiple climate systems including the East Asian Summer Monsoon (EASM), the Indian Summer Monsoon (ISM), the East Asian Winter

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Monsoon (EAWM), and the subtropical jet stream (i.e., the westerly jet), and is therefore quite complex (Chen et al., 2008; An et al., 2012).

The geographical and seasonal distribution of precipitation on the TP is influenced by the monsoon systems and the westerly jet, the extents of which have varied at seasonal, inter-annual, and glacial-interglacial timescales (Tian et al., 2007; An et al., 2012; Yao et al., 2012). The mean position of the subtropical jet over the TP is notably different over central Asia than at other longitudes because it intensifies during the summer season, relative to the spring transition season, due to the seasonally specific spatial patterns of tropospheric warming and topographic influences (Schiemann et al., 2009). A brief overview of the seasonal progression is as follows: during winter, the subtropical jet is intense and positioned south of the TP. During spring the jet moves northward across the TP; its position is highly variable and its intensity is diminished. During summer, the jet moves to the north of the TP and stabilizes with respect to its meridional position. In autumn, the jet once again moves southward across the TP, destabilizes and loses intensity (although it is more intense than in the spring season) (Schiemann et al., 2009). Based on reanalysis data, Schiemann et al. (2009) found that during the late spring, a northerly (southerly) jet position in the Tibetan Plateau regions is associated with both higher (lower) precipitation upstream and to the north of the plateau and lower (higher) precipitation over the plateau. Thus, changes in the timing and nature of seasonal jet migration, and the related strength of the summer monsoons, are expected to have an impact on the distribution of precipitation across the TP.

Precipitation changes did not occur uniformly across the TP during the Holocene. Compilations of paleolimnological data across the TP (Chen et al., 2008) indicate that changes in effective moisture in the southern and eastern TP generally tracked monsoon intensity during the Holocene, with wetter conditions during the early to middle Holocene and drier conditions during the late Holocene. By contrast, in the western and northern TP effective moisture showed the opposite trend (drier in the early Holocene and wetter during the middle Holocene), implying that the hydroclimate of the western and northern TP has not been driven by changes in monsoon-delivered moisture. Furthermore, the complied paleolimnological records in Chen et al. (2008) implied when the average position of the jet was located further south and the monsoon rarely reached the interior TP, a considerable amount of precipitation still occurs in the northern TP. Indeed, climate records in East and South Asia show that monsoon intensity has weakened since the middle Holocene (Dykoski et al., 2005; Wang et al., 2005) and that the average position of the ITCZ migrated farther south (Haug et al., 2001; Fleitmann et al., 2007; Yancheva et al., 2007; Schneider et al., 2014). This suggests that the extent of monsoon precipitation on the TP has diminished since the middle Holocene.

Oxygen and hydrogen isotope ratios in precipitation are integrated tracers of atmospheric processes (Dansgaard, 1964; Craig and Gordon, 1965) with applications for atmospheric dynamics (Vimeux et al., 2005; Tian et al., 2007; Risi et al., 2008, 2010; Gao et al., 2011; Vimeux et al., 2011), hydrology (Landais et al., 2010; Gao et al., 2013), cloud processes (Schmidt et al., 2005; Risi et al., 2008, 2010), and quantitative estimations of past regional climate change from natural archives (Thompson et al., 2000). Over the TP, precipitation $\delta^{18}O$ values reflect integrated effects of the westerly jet and Indian monsoon, combined with local moisture recycling, which is characterized by evaporation, convection, and droplet re-evaporation (Tian et al., 2007; Yao et al., 2013). Therefore, precipitation isotope records from different regions across the Plateau can provide valuable insight into past changes in hydrologic conditions and the past dynamics of the monsoons and westerly jet.

Here we present records of compound specific hydrogen isotope (D/H) ratios of sedimentary leaf waxes from sediment cores of three lakes (Bangong Co on the western TP, Lake Qinghai in the northeastern TP and Linggo Co in the northern TP) in order to document and investigate variations in precipitation isotopes across the TP since the Late Pleistocene. We examine the differences among the records of leaf wax δD values, together with previously published records of past hydrologic change, to examine the controls on TP hydrology and to elucidate mechanisms for climate change on the Tibetan Plateau since the Late Pleistocene.

2. Samples and methods

2.1. Sediment core collection

Sediment cores for leaf wax D/H analysis were collected from three lakes, Bangong Co, Linggo Co, and Lake Qinghai. Bangong Co and Lake Qinghai are located near the northern limit of modern summer monsoon. Linggo Co is currently located beyond the influence of summer monsoon in a region that is largely influenced by the westerly jet (Tian et al., 2007).

Bangong Co (also called Pangong Tso; 33°42′ N, 78°41′ E, 4220 m asl) is a dimictic lake of tectonic origin in western TP (Fig. 1) (Wang et al., 2014). The lake is 627 km^2, of which 413 km^2 (the eastern lake basin) is located in the western Tibetan Autonomous Region. The lake's watershed is 25,787 km^2. The maximum depth of the lake is 41.7 m. According to NASDE (Ngari Station for Desert Environment Observation and Research, Chinese Academy of Sciences) monitoring data from 2010 to 2014, mean annual precipitation is 87 mm, over 80% of which falls during summers (June–September) coincident with the summer monsoon. Mean annual air temperature is 2 °C. The eastern lake basin of Bangong Co is mainly fed by meltwater from glaciers. A 680 cm long sediment core (BGC-2011) was retrieved in 2011 at a water depth of 25 m.

Lake Qinghai (37°01′ N, 100°12′ E, 3194 m a.s.l., Fig. 1), the largest lake in China, is a closed-basin, brackish lake (An et al., 2012). Mean annual precipitation is 373 mm, with more than 70% occurring in summer. A 523 cm long sediment core, QH2005, was retrieved at 24 m water depth in the southeastern lake basin in 2005.

Linggo Co (88°35′ E, 33°51′ N, 5059 m a.s.l., Fig. 1) is located ~40 km west of, Purogangri Glacier, the largest ice field on the northern TP. The lake is mainly fed by glacial meltwater and precipitation. Linggo Co is ~100 km^2 with maximum depth of 70 m.

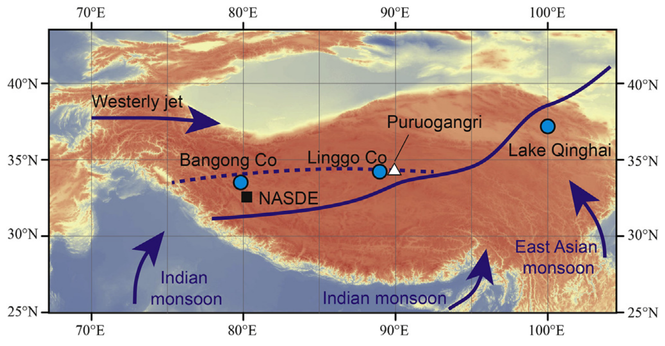

Fig. 1. Locations of Bangong Co in the western Tibetan Plateau (TP), Linggo Co in the northern TP and Lake Qinghai in the northeastern TP. Solid line represents the transition between East Asian monsoon, Indian monsoon and the westerly jet (Gao, 1962). Dashed line represents the boundary based on precipitation stable isotopes in Tian et al. (2007). NASDE (solid square) represents Ngari Station for Desert Environment Observation and Research, Chinese Academy of Sciences. White triangle represents Puruogangri Glacier.