Holocene climate controls on water isotopic variations on the northeastern Tibetan Plateau

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ARTICLE INFO

ABSTRACT

On the Tibetan Plateau, applications of δD and $\delta^{18}O$ values in paleoclimate studies tend to be complicated due to multiple processes influencing isotopic compositions in paleoclimatic archives. In this study, isotopic compositions of modern waters in the eastern Qaidam Basin on the northeastern Tibetan Plateau, and δD values of n-fatty acids (n-FA δD) from a sediment core at Hurleg Lake were systematically analyzed to infer hydroclimate controls during the Holocene. The modern water isotopic results show a major contribution of snowmelt water originating from high-elevation mountains to the north of the Qaidam Basin via river and groundwater discharge, and the importance of evaporation in affecting lake water budget in this region. n-C_{26} FA δD values tend to be more negative at millennial-scale warm-dry periods during the Holocene, and vice versa, opposite to what is commonly expected. Assisted with modern water isotopic results, we infer amplified contribution of snowmelt water to the soil water around this open lake system at warm-dry periods. Meanwhile, changes in n-C_{16} FA δD values at Hurleg Lake reflect the evolution of isotopic compositions of lake water, thus we use the isotopic difference between n-C_{26} and n-C_{16} FA ($\Delta D_{C16-C26}$) to infer hydroclimate and evaporation variations in this region. Based on our data, relatively low n-C_{26} FA δD and n-C_{16} FA δD values at 10–6 cal ka BP indicate large contribution of snowmelt water into the lake during the Holocene Climate Optimum. After 6 cal ka BP, changes in evaporation became the major control on lake hydrology and led to larger fluctuations of $\Delta D_{C16-C26}$. Our study highlights the importance of systematic analysis on modern processes before using stable isotopes for paleoclimate reconstructions, and demonstrates that δD difference between long-chain and short-chain n-FA might be an effective way to better understand the controlling factor of hydrological variations in a climatic complex region like the Tibetan Plateau.

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1. Introduction

Stable isotopes serve as a powerful tool for understanding past climatic changes. In polar regions, $\delta^{18}O$ records from ice cores have been widely interpreted as past temperature variations (e.g. Petit et al., 1999; Johnsen et al., 2001). In tropical monsoon regions, $\delta^{18}O$ in climate archives including speleothems have been used as proxy for monsoon intensity and thus monsoon precipitation (e.g. Dykoski et al., 2005; Wang et al., 2005). Around the high-altitude Tibetan Plateau, however, interpretation of stable isotopes in paleoclimatic archives is more complicated. For instance, the $\delta^{18}O$ of some ice cores from the Tibetan region (e.g. Dunde ice core) is not only controlled by air temperature as conventionally interpreted, but also influenced by monsoon precipitation (Davis et al., 2005). Also, $\delta^{18}O$ data from Kesang Cave (Cheng et al., 2012) at Tianshan Mountain to the north of the Tibetan Plateau shows an anti-phased relation with those from the nearby Guliya ice cap (Thompson et al., 1997) at the beginning of interglacials, and thus cannot be simply interpreted by the temperature effect only as the Guliya ice cap record does (Thompson et al., 1997). It is possible that incursions of Asian summer monsoon rainfall and moisture in the region during

the high insolation times may play an important role in changing the $\delta^{18}O$ signals in Kesang Cave (Cheng et al., 2012). Although stable isotopes derived from lake sediments in this arid region have also been widely used for reconstructions of past hydroclimate variations around the Tibetan Plateau, the interpretation of the isotopic data is also further complicated by multiple factors influencing isotopic fractionation, such as temperature effect and amount effect on precipitation isotopes, evaporation effect under dry climate (including evaporation on lake water, rain drops, and vegetation, etc.) and probable contributions of snow or glacial melt water input from nearby high-elevation mountains (e.g. Liu et al., 2008a; Henderson et al., 2010; Wang et al., 2013).

In order to better understand past hydroclimate variations in this climatically sensitive region, information about inputs from various water sources and effects of evaporation need to be separated. Compound specific δD of lipids preserved in lake sediments might serve as a potential proxy for past hydroclimate changes, since terrestrial and aquatic plants/algae use their own ambient water for lipid biosynthesis (e.g. Yapp and Epstein, 1982; Sessions et al., 1999; Sachse et al., 2004, 2012; Aichner et al., 2010; Duan et al., 2014; Rao et al., 2014; Yu et al., 2014; Aichner et al., 2015; Yao et al., 2015; Thomas et al., 2016). Many studies have used δD values of mid- and long chain n-alkanes to reconstruct individual isotopic information of aquatic and terrestrial source water (e.g. Mügler et al., 2008; Duan et al., 2014; Rao et al., 2014). It has been suggested that there exists more distinguished difference in the chain-length distribution of n-fatty acid (FA) between the aquatic and terrestrial plants (Wang and Liu, 2012). In lake sediments, δD values of long-chain n-FA (e.g. n-C_{26} to n-C_{30}) can be used to track the isotope signal of terrestrial source water and thus local precipitation (Sternberg, 1988; Sachse et al., 2004; Liu and Huang, 2005; Smith and Freeman, 2006; Huang et al., 2007; Wang and Liu, 2012), while δD values of short-chain n-FA (e.g. n-C_{16} to n-C_{20}) could record the isotopic composition of lake water which carries the isotopic imprints of both inflowing source water and evaporative enrichment (Cranwell et al., 1987; Huang et al., 2002; Wang and Liu, 2012). Since the biosynthetic fractionation of the lipids to source water is similar in both terrestrial plants and aquatic organisms (Sachse et al., 2006), the δD difference between short-chain n-FAs and long-chain n-FAs can potentially remove the isotopic information of source water from the isotopic signal, and assess the magnitude of lake water evaporation relative to source water, especially in arid regions with limited precipitation but strong evaporation (Sachse et al., 2006; Mügler et al., 2008). This method is particularly helpful for open-lake systems in arid areas where lake hydrology could be dominated by either evaporation or inflow water input, since lake water isotope composition alone won't be able to determine which factor is more important.

A systematic analysis on isotopic processes of regional hydrology is necessary before using n-FA δD values for paleoclimate reconstructions in a specific region. Previous studies of n-FA δD values of different chain lengths have been largely focused on modern surface samples from lake sediments, soils and plants (e.g. Sachse et al., 2006; Wang and Liu, 2012). δD values of both short-chain and long-chain n-FA are influenced by multiple factors, making it difficult to fully delineate the mechanism of isotopic fractionation process (e.g. Duan et al., 2014; Yu et al., 2014; Aichner et al., 2015; Yao et al., 2015), which in turn would prevent us from applying down-core isotopic records to paleohydroclimatic reconstruction. However, if we have already extracted climatic information from a sedimentary core using different proxies, we may infer controlling factors of isotopic fractionation process through time using the same core.

Climate in the Holocene has been characterized by a gradual cooling trend in the Northern Hemisphere high and mid-latitude regions and by a gradual drying trend in the monsoonal region (Mayewski et al., 2004; Dykoski et al., 2005). However, the Arid Central Asia experienced increased humidity in the mid-Holocene, which was anti-phased with changes in the Asian monsoonal region (Chen et al., 2008). In addition to the long-term trend, many studies on lakes in the Arid Central Asia

have revealed hydrological variations at millennial-scale (e.g. Rhodes et al., 1996; Mischke et al., 2005; Mischke and Wünnemann, 2006). In previous studies, Holocene temperature (Zhao et al., 2013) and moisture (Zhao et al., 2010) reconstructions based on a sediment core taken from Hurleg Lake suggested a distinct millennial warm-dry association throughout the Holocene and an increase in regional climate variability after the mid-Holocene. In this study, we examine δD and $\delta^{18}O$ compositions of modern water samples from freshwater and saline lakes, groundwater, rain, puddles, and rivers in the eastern Qaidam Basin on the northeastern Tibetan Plateau. Then, we report δD records of n-C_{16} and n-C_{26} FAs extracted from a Holocene sediment core at Hurleg Lake. Together with the alkenone-based salinity record from %$C_{37:4}$ and the previously published temperature (Zhao et al., 2013) and lake-level (Zhao et al., 2010) data from the same sediment core, we aim to infer main water sources to Hurleg Lake, to reconstruct hydrogen isotopic signals in terrestrial (long-chain n-FA) and lacustrine (short-chain n-FA) source waters, to infer controlling factors of δD values in terrestrial and lacustrine source waters, and to better understand Holocene hydroclimate variations on the northeastern Tibetan Plateau.

2. Material and methods

Hurleg Lake (37°17′ N, 96°54′ E; elevation 2817 m above sea level, Fig. 1A) is a freshwater lake located in the Qaidam Basin on the northeastern Tibetan Plateau. The lake is mainly fed by the Bayin River, the Balegen River (prior to the reservoir construction), and groundwater originating in the high mountains to the north of the basin. This region is likely influenced by the westerly rather than the Asian Summer Monsoon since the early Holocene, as indicated by modern meteorological studies (Tian et al., 2003) and proxy records (Chen et al., 2010; Zhao et al., 2010, 2013; He et al., 2013). Mean annual air temperature, precipitation and potential evaporation in this region are 1.4 °C, ~160 mm and ~2000 mm, respectively, as documented by the instrumental data from the nearby Delingha meteorological station (~30 km to the east, Fig. 1B; Zhao et al., 2010).

A total of 56 water samples were collected from rain, lakes, rivers, springs/wells, and puddles around the Hurleg Lake region in the summers of 2005, 2006 and 2007 (Fig. 1C, Supplemental Table S1). Core HL06-1 was obtained in July 2006 at 7.6 m water depth using a UWITEC corer. Detailed chronological information has been described previously (Zhao et al., 2010, 2013). The age model was established through AMS-^{14}C dates on the aquatic plant *Ruppia* from selected intervals, after correction of a 2758-year reservoir effect determined by the age difference between ^{14}C and ^{210}Pb dates from the top part of core HL06-1 (Zhao et al., 2010). Based on the derived chronology published previously (Zhao et al., 2013), core HL06-1 contains continuous sequence through the past 10,500 years, with a mean sedimentation rate of ~0.083 cm/year. As core HL06-1 lacks dating control before 7.4 cal ka BP, here we mainly focus on the isotopic variability over the last 8000 years. Consequently, we achieved centennially-resolved records, with ~120-year sampling resolution for the last 7400 years and ~500-year sampling resolution before 7.4 cal ka BP.

A total of 243 sediment samples were analyzed for n-FAs and alkenones and ~70 samples were further chosen for compound specific δD analysis. The samples were prepared following the standard procedures from Wang and Liu (2012). The total lipids were extracted from the freeze-dried sediments with organic solvents (dichloromethane:methanol = 9:1, v/v). After being hydrolyzed by 6% potassium hydroxide in methanol solution, the neutral fraction was extracted with n-hexane. The basic solution was acidified to pH < 1 to extract the carboxylic acid fraction with n-hexane. The neutral fraction was then separated into three fractions with silica gel column chromatography using eluents of n-hexane, dichloromethane and methanol, while the dichloromethane fraction contains alkenones. The acid fraction samples were heated to 60 °C with the 5% acetyl chloride in