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Spatial distribution and controlling factors of stable isotopes in meteoric waters on the Tibetan Plateau: Implications for paleoelevation reconstruction

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A B S T R A C T

Debates persist about the interpretations of stable isotope based proxies for the surface uplift of the central–northern Tibetan Plateau. These disputes arise from the uncertain relationship between elevation and the $\delta^{18}O$ values of meteoric waters, based on modern patterns of isotopes in precipitation and surface waters. We present a large river water data set (1,340 samples) covering most parts of the Tibetan Plateau to characterize the spatial variability and controlling factors of their isotopic compositions. Compared with the amount-weighted mean annual oxygen isotopic values of precipitation, we conclude that river water is a good substitute for isotopic studies of precipitation in the high flat (e.g., elevation >3,300 m) interior of the Tibetan Plateau in the mean annual timescale. We construct, for the first time based on field data, contour maps of isotopic variations of meteoric waters ($\delta^{18}O$, δD and d-excess) on the Tibetan Plateau. In the marginal mountainous regions of the Plateau, especially the southern through eastern margins, the $\delta^{18}O$ and δD values of river waters decrease with increasing mean catchment elevation, which can be modeled as a Rayleigh distillation process. However, in the interior of the Plateau, northward increasing trends in $\delta^{18}O$ and δD values are pronounced and present robust linear relations; d-excess values are lower than the marginal regions and exhibit distinct contrasts between the eastern (8‰–12‰) and western (<8‰) Plateau. We suggest that these isotopic features of river waters in the interior of the Tibetan Plateau result from the combined effects of: 1) mixing of different moisture sources transported by the South Asian monsoon and Westerly winds; 2) contribution of moisture from recycled surface water; and 3) sub-cloud evaporation. We further provide a sub-cloud evaporation modified Rayleigh distillation and mixing model to simulate the isotopic variations in the western Plateau. Results of this work suggest that stable isotope-based paleoaltimetry studies are reliable in the southern through eastern Plateau margins; towards the central–northern Plateau, this method cannot be applied without additional constraints and/or large uncertainties.

1. Introduction

Observations that the isotopic values ($\delta^{18}O$ and δD) of meteoric waters (e.g., precipitation and river water) decrease with increasing elevation (Dansgaard, 1964; Garzione et al., 2000b; Gonfiantini et al., 2001; Poage and Chamberlain, 2001; Rozanski et al., 1993) and that authigenic carbonates can preserve the isotopic composition ($\delta^{18}O$) of paleo-meteoric waters (Cerling and Quade, 1993; Hoke et al., 2009; Talbot, 1990), led to the application of stable isotope-based paleoaltimetry to reconstruct the surface uplift history of orogenic belts and plateaus (Chamberlain and Poage, 2000; Garzione et al., 2000a; Rowley et al., 2001). Applications of this method in the southern Tibetan Plateau yield consistent results between different researchers (e.g., Currie et al., 2005; Ding et al., 2014; Garzione et al., 2000a; Rowley et al., 2001; Saylor et al., 2009), that also agree well with other paleoelevation proxies, such as foliar physiognomy and clumped isotope studies (Huntington et al., 2014; Spicer et al., 2003). However, using the same method to interpret topographic growth in the central–northern Tibetan Plateau is debated. For example, paleoelevation estimations for the Eocene and Miocene east Hoh Xil basin could differ by more than 3,500 m and 4000 m, respectively (Bershaw et al., 2012; Cyr et al., 2005; Polissar et al., 2009; Quade et al., 2011). To a large extent, these disputes arise from the uncertain relationship between elevations and $\delta^{18}O$ values

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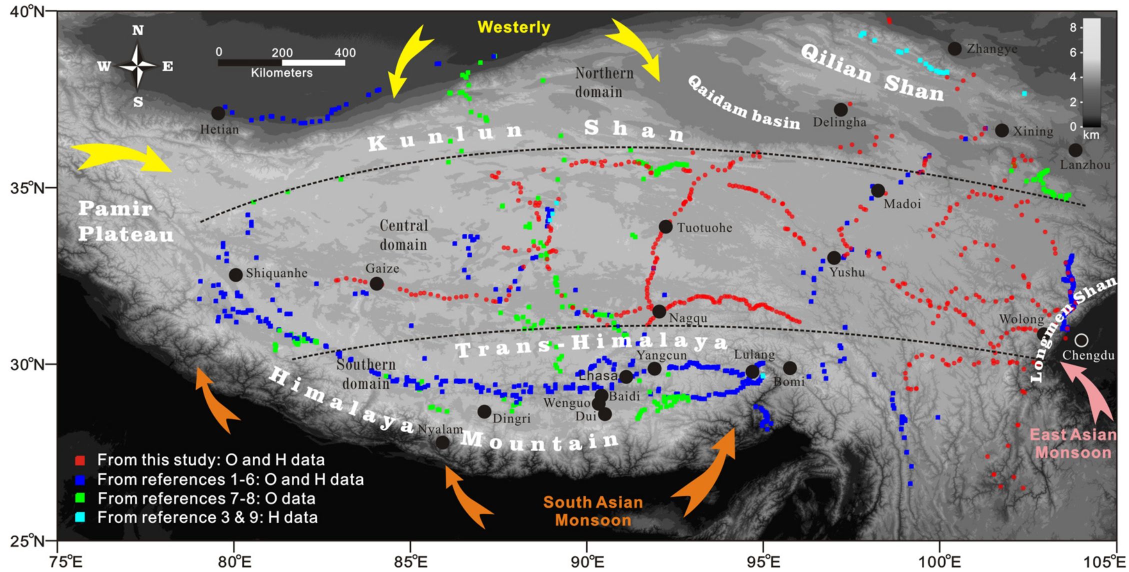

Fig. 1. Topographic relief map of the Tibetan Plateau, showing river water sampling locations: Red dots, from this study; Blue, green and cyan squares, from literature 1–9. Big thick arrows indicate major external air masses of the Tibetan Plateau (brown: South Asian monsoon; pink: East Asian monsoon; yellow: Westerlies; Araguás-Araguás et al., 1998). Large white letters are major mountain chains. Two east–west trending dashed lines are boundaries between three isotopic domains (northern, central and southern; Yao et al., 2013). Large black dots are precipitation monitoring stations. References: 1, Bershaw et al., 2012; 2, Hoke et al., 2014; 3, Hren et al., 2009; 4, Liu, 2014; 5, Quade et al., 2011; 6, Xu et al., 2014; 7, Ding et al., 2009; 8, Garzione et al., 2004; 9, Bai et al., 2012. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

of meteoric waters associated with competing fractionation processes in this deep continental setting (Bershaw et al., 2012; Hren et al., 2009; Tian et al., 2007; Yao et al., 2013), which result in large deviations from the isotopic values predicted from a simple Rayleigh distillation process on which stable isotope-based paleoaltimetry is based (Rowley and Garzione, 2007; Rowley et al., 2001).

This study addresses the spatial distribution and controlling factors of meteoric water isotopes on the Tibetan Plateau. As a direct condensate from the atmosphere, precipitation is the most commonly used source for studying meteoric waters. However, due to the limited and uneven distribution of monitoring stations on the Tibetan Plateau (Fig. 1), precipitation is a less ideal object to study isotopic variations on a plateau scale. In situations like this, surface waters, especially river water, may provide a reasonable substitute for precipitation. River water is mainly supplied by precipitation that infiltrates the groundwater table or flows overland. River water can capture the isotopic compositions of local precipitation (Kendall and Coplen, 2001; Rowley and Garzione, 2007). In addition to the fact that river waters are much easier to sample, their isotopic compositions represent the amount-weighted average value of precipitation in the upstream catchment area. If sampled outside of the main rainy season, the isotopic compositions of stream water reflect those of groundwater input. Although infiltration to groundwater might be biased to times when precipitation is greater than potential evaporation, it has been argued that the isotopic compositions of river water can provide an amount-weighted integration of annual precipitation, information that is useful in constructing the elevation-δ^{18}O relation for stable isotope-based paleoaltimetry studies (Rowley and Garzione, 2007).

Several studies focusing on river waters have been carried out on the Tibetan Plateau (Bershaw et al., 2012; Ding et al., 2009; Hren et al., 2009; Liu, 2014; Quade et al., 2011; Xu et al., 2014). These studies confirm the competing influence of the South Asian monsoon and Westerly moisture sources (Hren et al., 2009), as well as the important role of local surface water recycling (Bershaw et al., 2012). However, large gaps in river water sampling from the western, central and eastern Plateau (Fig. 1) leave challenges in interpreting the controlling factors for isotopic variations across the whole Tibetan Plateau region.

In this study, we carried out wide-spread sampling of river waters in parts of the Tibetan Plateau that still lack data (Fig. 1, red dots). In combination with previous published river water data (Bershaw et al., 2012; Ding et al., 2009; Hoke et al., 2014; Hren et al., 2009; Liu, 2014; Liu et al., 2014; Quade et al., 2011; Xu et al., 2014), this large data set improves our knowledge of the spatial variability of stable isotopic compositions of river waters on the Tibetan Plateau, and also allows us to address the following major questions: 1) Is river water a good substitute for precipitation to study the spatial isotopic variations on the Tibetan Plateau on the mean annual timescale? and 2) What are the controlling factors for isotopic variations of meteoric waters (river water/precipitation) on the Tibetan Plateau? We address the first question through a comparison of river water data with available precipitation data, and the second question by looking at the spatial variations of δ^{18}O, δD and d-excess values. Finally, with this new understanding, we discuss the implications for stable isotope-based paleoaltimetry studies in the Tibetan Plateau.

2. Geography and moisture transport

2.1. Geography

The Tibetan Plateau is the highest and largest topographic feature on Earth (Fig. 1). Except the northeast and southeast, all the other margins are bounded by very high elevation (>6000 m) and steeply sloped (gradients up to 6%) mountain chains; such as the Himalayan Mountains, Longmen Shan, and Kunlun Shan ("Shan" means mountain in Chinese) (Fig. 1). The eastern Plateau (mainly east of 93°E) is characterized by rugged terranes, with high-discharge, south–southeastward flowing rivers cutting deeply (2000–3000 m) into the landscape. On the contrary, the western Plateau is relatively flat, with most regions between 4500–5000 m. Interestingly, this east–west topographic difference is also accompanied by difference in annual precipitation amount: high in the