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Stable isotopic composition reveals the spatial and temporal dynamics of discharge in the large river of Yarlungzangbo in the Tibetan Plateau

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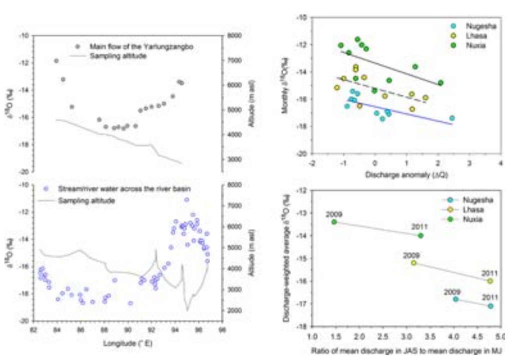
HIGHLIGHTS

- Spatio-temporal isotopic variability of the Yarlungzangbo flow was investigated.
- Spatial isotopic patterns of river flow and precipitation in the basin are consistent.
- Input of monsoon precipitation causes significant decreases in river $\delta^{18}O$ in summer.

GRAPHICAL ABSTRACT



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ABSTRACT

Spatial and temporal variability in stable isotopic compositions ($\delta^{18}O$ and δD) in river water of the Yarlungzangbo was investigated to identify major hydrological processes along the river channel and evaluate the isotopic response to discharge variation. The results show geographic, distinct isotopic evolutions in the Yarlungzangbo system. Along the main stem, river $\delta^{18}O$ exhibits a decreasing trend from the headwaters to the middle reach but an increasing one from the middle to the lower reaches, and main flows demonstrate much greater $\delta^{18}O$-δD slope and intercept compared to the global meteoric water line (GMWL) and reported local meteoric water lines (LMWLs) for sites within the basin. These results are found to be consistent with the isotopic characteristics of stream and river waters collected across the entire drainage basin. Water mixing appears to be the dominant hydrological process along the Yarlungzangbo, and the pattern of isotopic change in individual river reaches closely reflects that of precipitation in corresponding part of the river basin. The isotopic variability along the main stem observed during the synoptic survey is evidenced to hold through time by a time-series investigation at three key hydrological stations. River water at such three stations shows a strong isotopic response to discharge variability. In general, river $\delta^{18}O$ tends to be negatively correlated with discharge, highlighting a typical monsoon precipitation-driven isotope-discharge pattern. Specifically, we found their individual discharge-weighted average $\delta^{18}O$ values likely vary in a similar rate with the ratio of mean discharge in monsoon season (JAS) to that in pre-monsoon season (MJ) on a yearly basis, indicating a specific relationship between average river isotopic composition and discharge seasonality throughout their drainage areas (i.e. the middle-lower Yarlungzangbo basin). This study thus demonstrates the usefulness of isotopic data for assessing hydrodynamics over a less explored, complex and high-altitude large river catchment.

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1. Introduction

Investigations of water sources, flow paths and hydrological response to climate change in large river systems that originate in the Tibetan Plateau (TP) are critical for answering questions relating to regional water availability, water sustainability, biogeochemical cycling and even changes of regional atmospheric circulation pattern (e.g. Bookhagen et al., 2005; Immerzeel et al., 2010; Karim and Veizer, 2002; Singh et al., 2013; Su et al., 2016; Yao et al., 2013; Yao et al., 2012; Zhang et al., 2013). Of specific interest is the spatial and temporal variability in hydrodynamics as well as the mechanisms behind within their drainage areas. The Yarlungzangbo (i.e. the upper Yarlungzangbo-Brahmaputra River), which flows in the southern TP, is the highest large river of the world, and it contributes a large amount of freshwater input to the Bay of Bengal (BOB) which is assumed to have profound effects on the Indian summer monsoon (ISM) (Breitenbach et al., 2010; Howden and Murtugudde, 2001; Sengupta et al., 2006; Sengupta et al., 2008). However, our understanding of hydrological fluxes in the Yarlungzangbo system and their response to basin-specific characteristics is still limited due to a lack of systematic investigations and measurements.

The oxygen and hydrogen stable isotopes ($\delta^{18}O$ and δD) demonstrate great potential to trace climatological and hydrological processes, and have been extensively used in water cycle research in both natural and urban settings (e.g. Bowen et al., 2007; Breitenbach et al., 2010; Gat, 1996; Gibson et al., 2016; Kendall, 1991; Lachniet and Patterson, 2002; Tian et al., 2007; Tipple et al., 2017; Yi et al., 2010; Yuan and Mayer, 2012). Previous isotopic investigations across the Yarlungzangbo basin mainly focused on mechanisms of precipitation formation (especially the moisture sources and topographical effect) in its central and eastern parts. For instance, isotopic composition in precipitation in the eastern Yarlungzangbo basin exhibits a profound "altitude effect", primarily due to the orographic lifting and adiabatic cooling of monsoonal moisture in summer (Hren et al., 2009; Gao et al., 2011; Ren et al., 2017b; Yang et al., 2012b); monsoonal moisture can be also transported through low passes in the central Himalayas and then reaches the central Yarlungzangbo basin (Kang et al., 2002; Ren et al., 2017a; Tian et al., 2007; Yu et al., 2016); isotopic investigations also revealed the significant influence of the westerlies-derived moisture in the western Yarlungzangbo basin (Hren et al., 2009; Ren et al., 2016). The observations of these studies suggest that mechanism of precipitation formation varies dramatically across the Yarlungzangbo basin. In order to better understand the water sources and hydrodynamics of the Yarlungzangbo, it is necessary to examine the patterns of isotopic composition in both river flows and precipitation over the drainage catchment. Nevertheless, systematic investigation and interpretation of isotopic signatures of river flow in this large river system with respect to climatic conditions, hydrological fluxes and flow quantity remain scarce.

This study presents oxygen and hydrogen isotopic data of surface waters collected through two synoptic surveys across the Yarlungzangbo basin. Major controls on the spatial variability in isotopic composition of river flows along the main channel are described and identified. A time-series isotopic investigation was also conducted at three key hydrological stations to assess how water isotopic composition responses to discharge variability. Overall, this study documents the spatial and temporal variations of stable isotopic compositions in river water for characterizing major hydrodynamics over a high-altitude large river catchment.

2. Methods

2.1. Study area

The Yarlungzangbo is the highest large river of the world, with a mean discharge of >4000 m^3/s (Guan et al., 1984). It rises in the Jiemayangzong Glacier (>5100 m asl) in the northern slope of the western Himalayas, flows eastward between the west-east trending mountain belts of the Himalayas and the Gangdise-Nyainqêntanglha, and then turns southward in the area near the eastern Himalayan syntaxis (Fig. 1a), with a length of ~2000 km and a catchment area of ~ 240,000 km^2. Annual precipitation in the Yarlungzangbo basin is generally dominated by the Indian summer monsoon (ISM) circulation (Fig. 1a) (e.g. Gao et al., 2013; Hren et al., 2009; Tian et al., 2001b, 2007; Yu et al., 2016), which develops closely linked to the movement of the Inter-Tropical Convergence Zone (ITCZ) (Gadgil, 2003). However, its western part is significantly influenced by the westerlies (Hren et al., 2009; Ren et al., 2016). Due to the block of the Himalayas, it is believed that monsoonal moisture penetrates into the southern TP mainly along major valleys around the eastern edge of the Himalayas, and produces heavy rainfall as it is orographically lifted and adiabatically cooled (Bookhagen et al., 2005; Hren et al., 2009; Yao et al., 2013). There is a clear west-east gradient in climate and hydrology across the Yarlungzangbo basin. In general, mean annual precipitation decreases westward from ~1000 mm near the eastern Himalayan syntaxis to ~200 mm in the headwaters. Aridity prevails north of the central and western Himalayas as a result of the rainshadow effect and/or a long distance from the ocean. Monthly precipitation at various sites along the west-east transect across this basin is presented in Fig. 2a. Apart from the easternmost part (e.g. Bomi) and headwaters (see Pulan, which is near the headwaters), annual precipitation predominantly occurs during the summer period (JJAS). An eastward increase in both spring (MAM) and summer precipitation is a notable climatic feature in the central-eastern Yarlungzangbo basin (e.g. from Lhaze, Lhasa, Nyingchi to Bomi, Fig. 2a). The large amount of spring precipitation in the eastern basin is indicative of a region-specific atmospheric circulation regime (Ren et al., 2017b; Yu et al., 2017).

At a rough catchment scale, this river can be approximately sectioned into three parts: the upper one is from the source to Saga and the major tributaries include the Mayouzangbo, Caiqu and Jiadazangbo; the middle one is from Saga to Qushui, with major tributaries of the Duoxiongzangbo and Nyangqu; the lower one is from Qushui to sites near the eastern Himalayan syntaxis, with major tributaries of the Lhasa River, Nyang River and Parlungzangbo. Guan et al. (1984) concluded that the annual total runoff of major tributaries of the Yarlungzangbo generally decreases towards the headwaters, with a similar trend to the annual precipitation across the basin. River flow in the Yarlungzangbo system is generally precipitation-dominated (Liu, 1999; Liu et al., 2007). On the basis of long-term data, discharge in the Yarlungzangbo shows a pronounced seasonality and mainly concentrates in summer (Gao et al., 2007). For example, ~71% of the annual runoff occurs during the June–September period at Nuxia in the lower Yarlungzangbo (Fig. 2c), in accordance with the high summer precipitation over the drainage catchment. Specifically, there are a large number of glaciers in the lower Yarlungzangbo basin (Fig. 1b), and both precipitation and glaciermelt are major river water sources in summer there (Yao et al., 2010). By contrast, meltwater and/or groundwater may be of particular importance in source areas of the Yarlungzangbo and its tributaries (Guan et al., 1984).

2.2. Water sampling and isotopic analysis

The sampling strategy in this study includes two synoptic surveys and a time-series sampling campaign. In June 2007, river flows of the Yarlungzangbo and its several major tributaries (including the Mayouzangbo, Caiqu, Lhasa River and Nyang River) were collected (Fig. 1c). Samples were collected in dry, clean 30 ml polyethylene bottles which were hand-dipped in flowing water at a water depth of 10–15 cm on the river shore. In case of post-sampling evaporation, bottles were filled in full and were then sealed with parafilm immediately. We also measured the electrical conductivity, pH and temperature of river waters using a handheld meter with probe (HANNA, Italy) on