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Stable isotope variations in precipitation over Deqin on the southeastern margin of the Tibetan Plateau during different seasons related to various meteorological factors and moisture sources

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ABSTRACT

This study investigated the variations of stable isotopes ($\delta^{18}O$ and δD) in precipitation at Deqin on the southeastern margin of the Tibetan Plateau. The results show that correlations between stable isotopes in precipitation and temperature vary during different seasons. In comparison, an apparent inverse correlation between stable isotopes and precipitation amount exists throughout different seasons. Hence, the "amount effect" appears to have significantly controlled the stable isotope variations in precipitation over the entire sampling period, rather than the "temperature effect". The overall temporal variations of $\delta^{18}O$ and δD in precipitation from Deqin are similar to those from a southern station at Xishuangbanna. Both stations demonstrate considerably depleted precipitation $\delta^{18}O$ values in the summer as a consequence of intense Asian summer monsoon activities. However, at Xishuangbanna, the occurrences of the timing and duration of the depleted $\delta^{18}O$ values, as well as the negative surface lift index values, occur earlier and last longer than those at Deqin. These results indicate that the Asian summer monsoon onset is later and that the duration of the monsoon activities is shorter at Deqin relative to Xishuangbanna.
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1. Introduction

Stable isotopes ($\delta^{18}O$ and δD) are widely used to determine various components of the hydrological cycle (Clark and Fritz, 1997; Birks and Edwards, 2009; He and Richards, 2015) and to identify different moisture sources in various regions (Sengupta and Sarkar, 2006; Deshpande et al., 2010; Salamalikis et al., 2015). $\delta^{18}O$ and δD in precipitation are influenced by numerous factors, including the condensation temperature, atmospheric humidity, air pressure, precipitation amount (Dansgaard, 1964; Rozanski et al., 1993), moisture sources (Araguás-Araguás et al., 2000; Bhattacharya et al., 2003; Aggarwal et al., 2004), and orographic terrain (Guan et al., 2009; Sinclair et al., 2011). In particular, some processes, such as moisture transport, rain–vapor isotopic exchange (Lawrence et al., 2004; Lee and Fung, 2008; Field et al., 2010), rainout (Araguás-Araguás et al., 1998), and evaporation/condensation (Dansgaard, 1964; Risi et al., 2008), strongly modify $\delta^{18}O$ and δD in precipitation. Kinetic effects influence the effective fractionation factors, and an excess value exists in the relationship between $\delta^{18}O$ and δD. The second-order isotope parameter deuterium excess, *d*-excess (or *d*), defined by Dansgaard (1964) as $d = \delta D - 8 \times \delta^{18}O$, is depicted as an index of deviation from the global meteoric water line (GMWL, $\delta D = 8.0\delta^{18}O + 10$) in $\delta^{18}O$ versus δD space (Fröhlich et al., 2002). Craig (1961) determined that the mean global meteoric water has a *d* of 10‰. *d* is a significant variable and is influenced by the rate of evaporation in the source area and the associated meteorological conditions (Merlivat and Jouzel, 1979).

Since 1961, the International Atomic Energy Agency (IAEA), in cooperation with the World Meteorological Organization (WMO), established over 1000 meteorological stations in more than 125 countries and territories for measuring the isotopic composition of monthly precipitation as part of the well-known GNIP program (Global Network of Isotopes in Precipitation). However, over 80% of GNIP stations collecting data are below 250 m a.s.l. (Araguás-Araguás et al., 2000), and the isotopic data are relatively sparse in high elevation regions, particularly in the Tibetan Plateau (Tian et al., 2001). Accordingly, in 1991, the Chinese Academy of Sciences (CAS) launched a project to establish a new observation network (the Tibetan Plateau Network of Isotopes in Precipitation, TNIP) to continually monitor stable isotope changes in precipitation on the Tibetan Plateau (Yao et al., 1996; Tian et al., 2001; Yu et al., 2007). Previous studies revealed that patterns of $\delta^{18}O$ in precipitation on the northern Tibetan Plateau are different from those on the southern

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plateau. On the northern Tibetan Plateau, the $\delta^{18}O$ values of precipitation exhibit a "temperature effect" due to the very weak influence of monsoon activities (Tian et al., 2003; Yu et al., 2008; Yao et al., 2013). On the southern Tibetan Plateau, the $\delta^{18}O$ values of precipitation exhibit an obvious "amount effect" during the observed years, resulting from strong Indian monsoon activities (Tian et al., 2001; Yu et al., 2008, 2015a; Yao et al., 2013). However, a positive correlation exists between $\delta^{18}O$ in precipitation and temperatures before the onset of the monsoon (Yu et al., 2008). Similar to the eastern Tibetan Plateau (Yu et al., 2006; Tian et al., 2008), stable isotopes in summer precipitation from the western Tibetan Plateau are more depleted compared to those in winter because of the effect of monsoon precipitation (Yu et al., 2007). In recent years, some scientists have focused on stable isotope variations in precipitation in the adjacent regions of the Tibetan Plateau, such as the northeastern margin of the plateau (Zhang et al., 2009; Wu et al., 2010; Zhao et al., 2011; Liu et al., 2014; Yu et al., 2014), southwestern China (Pang et al., 2006; Liu et al., 2007; Zhang et al., 2007) and northeastern India (Breitenbach et al., 2010). In comparison, a gap remains in understanding stable isotopes in precipitation on the southeastern margin of the Tibetan Plateau, such as in the Hengduan Mountains, because severe climatic conditions make observations difficult. On the Tibetan Plateau, from north to south, the patterns of $\delta^{18}O$ in precipitation vary, as mentioned above. However, understanding the variations of stable isotopes in precipitation on the southeastern margin of the Tibetan Plateau, which lies closer to the monsoon regions, is also necessary. In particular, investigating the factors that control stable isotopic compositions and variability in precipitation in the region will provide a better understanding of the moisture sources in the region and will improve interpretations of paleoclimate records from the southeastern margin of the Tibetan Plateau.

This study is the first to analyze the stable isotope compositions of event-based precipitation samples from the Deqin Meteorological Station in the Hengduan Mountains, which are located on the southeastern margin of the Tibetan Plateau. This paper discusses the seasonal changes of stable isotopes in precipitation, presents the relationships between stable isotopes and various meteorological factors, and determines the various effects (based on temperature, rainfall amount, and moisture sources) on the $\delta^{18}O$ and δD values of precipitation during different seasons.

2. Sampling sites, materials, and methods

The Deqin station (28° 28′ N, 98° 56′ E, 3350 m a.s.l.), located on the southeastern margin of the Tibetan Plateau, lies in a valley of the Hengduan Mountains (Fig. 1). The north–south mountains include a complex of north–south ridges and river valleys that rise between the southeastern margin of the Tibetan Plateau and the northwestern margin of the Yungui Plateau. Based on meteorological data from 1980 to 2012, the station has an average annual temperature of 5.9 °C, an average annual relative humidity of 70% and an average annual precipitation of 656 mm (Table 1).

The Institute of Tibetan Plateau Research (Chinese Academy of Sciences, Beijing, China) collected a total of 101 precipitation samples at Deqin in 2012. Rainfall from each precipitation event was collected and immediately sealed in clean, dry plastic bottles. All of the collected samples were refrigerated until analyzed. The precipitation sampling program recorded the duration of each precipitation event, surface temperature, relative humidity, and precipitation amount.

The Key Laboratory of Tibetan Environmental Changes and Land Surface Processes (Chinese Academy of Sciences, Beijing) measured the oxygen and hydrogen isotope ratios ($\delta^{18}O$ and δD) of all of the samples using a Picarro L1102-*i* Cavity Ring-down Spectroscopy (CRDS), with a precision of 0.1‰ and 0.6‰ for $\delta^{18}O$ and δD, respectively. Extensive calibration work was performed prior to sample measurements, including testing the stability of the analyzer, performing a series of tests to measure the memory effect, and determining the average memory factor (Yu et al., 2015b). The calibration followed the procedures established by Nelson (2000). The measured $\delta^{18}O$ and δD are expressed in parts per mil (‰) of their deviations, relative to Vienna Standard Mean Ocean Water (VSMOW2).

The wind and specific humidity fields for each precipitation event over Deqin were calculated by the National Centers for Environmental Prediction (NCEP) daily reanalysis of datasets, with a spatial precision of 2.5° from longitude–latitude grids (available at http://www.esrl.noaa.gov/psd/data/gridded/reanalysis/) (Kalnay et al., 1996). A subset of the results for 17 May, 23 July, and 5 October 2012 was selected to represent the pre-monsoon, monsoon and post-monsoon period conditions, respectively. To further understand the effect of the Asian summer monsoon activities and the lift effect of high mountains on the $\delta^{18}O$ and δD values of precipitation at Deqin, we selected Xishuangbanna as a reference station (21° 56′ N, 101° 16′ E, 750 m a.s.l.) for comparison, which lies on the southwestern margin of Yungui Plateau (Fig. 1). Sampling of precipitation events at Xishuangbanna occurred from January 2002 to December 2004 (Table 1) (Liu et al., 2007). In addition, based on a daily reanalysis of the datasets from the NCEP with a spatial precision of 2.5° from longitude–latitude grids (http://www.esrl.noaa.gov/psd/data/gridded/reanalysis/) (Kalnay et al., 1996), we calculated the surface lifted index in 2012 for Deqin and from 2002 to 2004 for

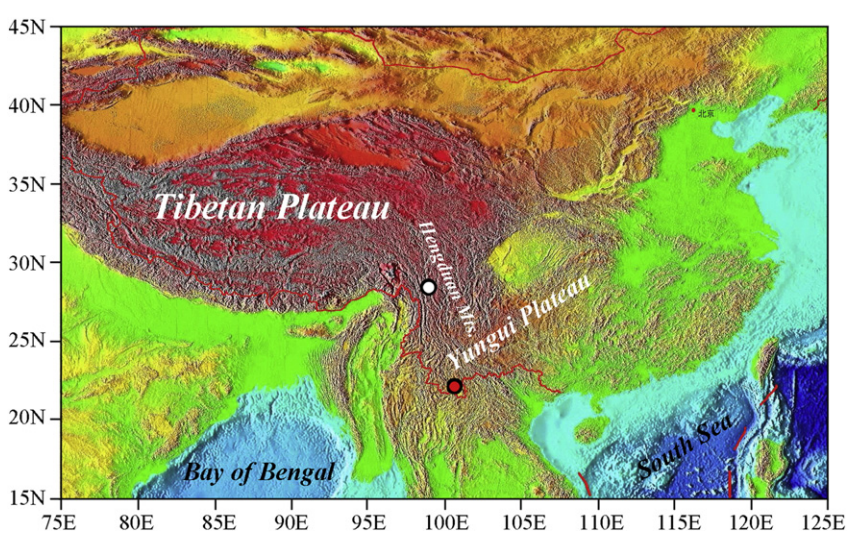

Fig. 1. Location of the Deqin sampling station (white dot) in the Hengduan Mountains on the southeastern margin of the Tibetan Plateau. Also shown is the comparative Xishuangbanna sampling site (red dot) on the southwestern margin of the Yungui Plateau.

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