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Stable isotopes in monsoon precipitation and water vapour in Nagqu, Tibet, and their implications for monsoon moisture

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ABSTRACT

Understanding climate variations over the Qinghai-Tibetan plateau has become essential because the high plateau sustains various ecosystems and water sources, and impacts on the Asian monsoon system. This paper provides new information from isotopic signals in meteoric water and atmospheric water vapour on the Qinghai-Tibetan Plateau using high frequency observation data over a relatively short period. The aim is to explore temporal moisture changes and annual variations at the onset and during the summer monsoon season at a transitional site with respect to the monsoon influence. Data show that high frequency and short period observations can reveal typical moisture changes from the pre-monsoon to the monsoon seasons (2010), and the large variation in isotopic signals in different years with respect to active/inactive periods during a mature phase of the monsoon (2011), especially inferring from the temporal changes in the *d*-excess of precipitation and its relationship with δ18O values, when higher *d*-excess is found in the pre-monsoon precipitation. In this transition zone on a daily basis, δ18O values in precipitation are controlled mainly by the amount of rainfall during the monsoon season, while temperature seems more important before the onset of monsoon. Furthermore, the "amount effect" is significant for night-time rain events. From comparison of signals in both the precipitation and water vapour, an inconsistent relationship between *d*-excess values suggests various moisture fluxes are active in a short period. The temporal pattern of isotopic signal change from the onset of the monsoon to the mature monsoon phase provides information about the larger circulation dynamics of the Asian monsoon.

1. Introduction

Stable oxygen and hydrogen isotopes in precipitation have long been used to trace atmospheric moisture origins, and the effects of the evaporation and condensation history of air masses (Dansgaard, 1964). To monitor the global isotopic composition of precipitation, the 'Global Network of Isotope in Precipitation' project was setup in 1961 by the International Atomic Energy Agency (IAEA) and the World Meteorological Organization (WMO) to intensively study the relation between atmospheric processes and isotopic information in water vapour and precipitation. With Lhasa station becoming member of this project in 1986, a dozen monitoring stations across the Qinghai-Tibetan Plateau (QTP) of China has gradually been setup to provide a continuous isotopic record of precipitation over the last 10 years (Yao et al., 2009). Because the isotopic composition of the precipitation on the plateau can vary at fine spatial and temporal resolution, field studies are also needed to capture dynamics of seasonal and even diurnal scales, especially the "transitional region" of the northern limits of the monsoon. This paper thus provides an example of detecting the intraseasonal variability of precipitation affected by land–atmosphere feedbacks.

For the Qinghai-Tibetan Plateau, spatial distribution and transport of total moisture is affected by the South Asian Summer Monsoon (SASM), transport of easterly (westerly) anomalies during the active (break) period of the SASM result in positive (negative) moisture anomalies over the southwest edge of the QTP and the Arabian Sea (Zhou et al., 2013). During the monsoon summer, the moisture transport trajectories are generally from the Arabian Sea and the Bay of Bengal to the southern boundary of the Plateau along the latitude belt; there are also moisture transport from upper layers and from the plateau surface evaporation. The former moisture transport results in low δ^{18}O while the latter results in relatively high values (Tian et al., 2001b). However, it is possible that there is mixture of moisture as the whole QTP is not subject

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to identical atmospheric circulation impacts. The Tanggula Mountains which range east and west along the latitude of 32–33°N make the study location a zone of transition in the precipitation regime between the north and south of the Tibetan plateau. Three regions can be demarcated in terms of their atmospheric circulation, these being the monsoon zone (south of 30°N), the transition zone (30–35°N), and the zone of westerly influence (north of 35°N) (Fig. 1, Yao et al., 2009; Tian et al., 2001c; Yu et al., 2006; Zhang and Yao, 1995; Zhang et al., 2003). In the westerly zone beyond the monsoonal influence, precipitation is mainly influenced by continental air masses, and the 'temperature effect' controls $\delta^{18}O$ values in precipitation, which shows a positive relationship between isotopic composition of precipitation and temperature as heavy isotopes rain out when the air mass travels inland, either to high latitudes or uplifted to higher altitudes (Clark and Fritz, 1997). By contrast, in the south, the 'amount effect' dominates the low $\delta^{18}O$ values related to the monsoon precipitation, which is a negative relationship between the amount of precipitation and the heavy isotope concentration (Gat, 1980; Wei and Lin, 1994). In the transition zone where monsoonal effects are weaker, the 'temperature effect' producing higher $\delta^{18}O$ values can be observed at the annual scale, before the monsoon onset and within a certain temperature range even during the monsoon (Liu et al., 2010; Yu et al., 2008, 2006).

Field research for this study was conducted in the transitional zone, where the monsoonal precipitation tends to be lower and its timing differs compared to the southern area, such as in Lhasa. Therefore, before and even during the monsoon season, continental moisture recycling may bring in precipitation other than moisture controlled directly by the SASM. Water is still a limit factor in the growing season when temperature favours growth and precipitation may influence the timing of greening and the duration of the growing season, and is essential for the alpine meadow to sustain its soil and water status, and to guarantee a livelihood for local herders (He, 2013). Pre-monsoon water provision, and variations in the onset, timing and length of inactive periods during the monsoon season have all impacted on the hydrological processes and vegetation growth (Park et al., 2012). Although studies along the North–South transect have detected the isotopic variations in precipitation subject to different regional climatic conditions, few have focused on temporal variations across the monsoon onset in the transition region, where long-term records show a significant contribution to the annual trend of an increase in pre-monsoon precipitation (He, 2013). Thus, observing the hydrological processes and isotope hydrology in the research area could contribute to testing future circulation modelling for the monsoonal system, which is likely subject to abrupt change although with low confidence in projections of a collapse (Collins et al., 2013).

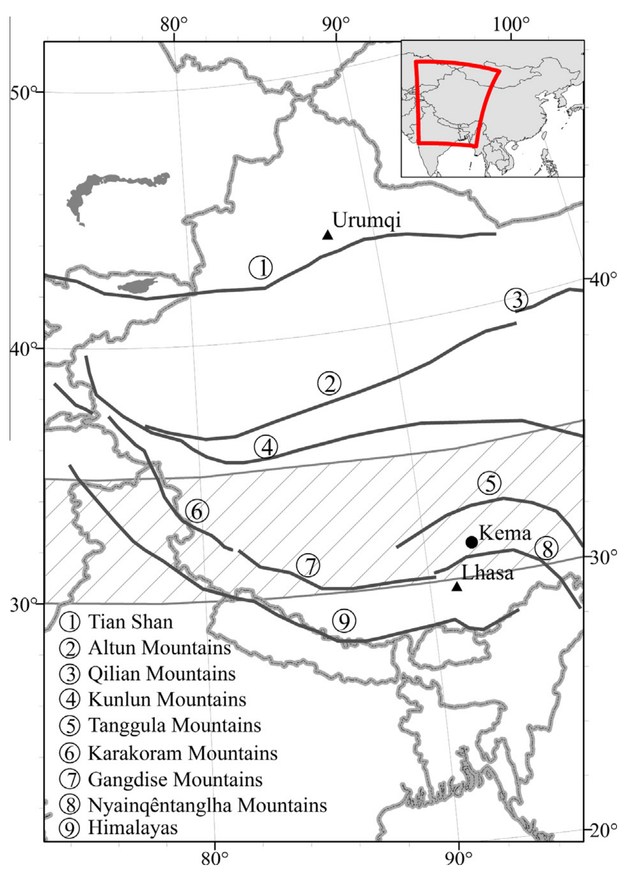

Fig. 1. Map of field location and the adjacent area of the Qinghai-Tibetan Plateau. Locations of major mountain ranges that impact on moisture transport into the plateau are illustrated. Transition zone from 30°N to 35°N is shaded.

In addition, recent studies have mainly been based on monthly or yearly averaged data, and there is a lack of detailed data to trace daily variations of moisture before and during the summer monsoon season. There is also limited knowledge about atmospheric water vapour on the Plateau, although it is thought that the isotopic composition of vapour is affected by precipitation events and large-scale moisture transport (Yu et al., 2005). To fill the gap, Kurita and Yamada (2008) conducted intensive observations using rawinsonde and stable isotope observations for various water sources in the Nagqu Basin, to investigate interactions between synoptic conditions and the hydrological cycle during the monsoon season. This was perhaps the first research conducted with a relatively high frequency measurement. Their research has confirmed that there is weak contribution of local evapotranspiration to the precipitation brought by a migratory frontal trough (TR-type) which mainly has moisture advected from remote areas, however, the moisture transferred from remote areas could moisten the lower-atmosphere through local evapotranspiration and contribute to water recycling in precipitation fell in a heat-low system (UH-type) and thermally induced regional circulation (NL-type). However, they also proposed that continuous long-term observation is necessary to understand more completely the role of moisture recycling during the entire monsoon season.

Therefore, we believe that the classification of rainfall and its moisture origin could be verified in this study, which has prolonged the research period from 2 weeks to 8 weeks. Based on previous research, this study aims to strengthen understanding of the temporal transition from the pre-monsoon to the monsoon season, in this transitional region, and to identify the factors controlling the variation of isotopic signals in precipitation on a daily timescale using high frequent observations. We also extend the use of isotopic data to high frequency sampling of atmospheric moisture which is only sampled by few researchers and focus on the moisture source dynamics during a short period. Specifically, this study detects the variation of moisture origin before and after the onset of the summer monsoon, as well as the active moisture recycling during the monsoon in this transition area, based on temporal change of stable isotopic signals in precipitation; it also compares variations of stable isotope signals in precipitation and atmospheric water vapour to identify possible moisture sources; the "temperature effect" and "amount effect" have been tested using event-based and daily-averaged isotopic values as well as meteorological records. The moisture dynamics are interpreted using two methods: (a) the δD–$\delta^{18}O$ relationship of moisture compared with the global meteoric water line (GMWL) (Merlivat and Jouzel, 1979), and the associated deuterium excess value (d-excess = $\delta D - 8\delta^{18}O$); and (b) the temporal variation of a single isotope ratio (i.e. $\delta^{18}O$).