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Asian monsoon variations revealed from stable isotopes in precipitation

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Abstract
To further our understanding of the Asian monsoon system, particularly the onset dates of monsoon sub-systems over their respective East Asian domains, we present an 8-year (2007–2014) dataset of oxygen isotopes of precipitation ($\delta^{18}O_p$) from three stations, Lulang and Nuxia in southeastern Tibetan Plateau (SETP) and Guangzhou in southeastern coastal China (SECN). The general agreement between isotopically identified monsoon onset dates with those identified by the meridional temperature gradient suggests that the initially sustained isotopic depletion is sensitive to the evolving thermal contrast between the Eurasian continent and the Indian Ocean. The 850 hPa meridional wind over nearby oceans is an efficient bridge linking isotopic variations in both regions with their respective monsoon sub-systems. The intensity of the South Asian High and tropical cyclone frequencies show stronger effects on isotopic depletion in the SECN than in the SETP and on monsoon onset timing over the South China Sea. Tibetan Plateau snow cover anomalies are significantly correlated with $\delta^{18}O_p$ in both regions on monthly timescales.

Keywords Asian summer monsoon · Stable isotopes in precipitation · Southeastern Tibetan Plateau · Southeastern coastal China · Wind circulations · Tropical cyclones · Snow cover anomalies

1 Introduction

The term "monsoon" refers to seasonal wind reversal and is characterized by onshore flow during summer (Wallace and Hobbs 1977). The monsoon is an important precipitation source, but in extreme cases poses threats to agriculture, industry and human livelihood. The Asian summer monsoon (ASM), which affects one-third of the world's population, is particularly pronounced in regions adjacent to the Indian Ocean (Wallace and Hobbs 1977). The ASM is characterized by large-scale circulation that includes several subsystems, including the South Asian summer monsoon and the East Asian summer monsoon (Conroy and Overpeck 2012; Wang and LinHo 2002), both of which have profound effects on China.

The differential land-sea thermal contrast leads to several monsoon onset phases in East Asia, although these are subject to various geomorphological features and heating conditions. The Tibetan Plateau (TP), an expansive and high-elevation land mass which is located in the mid-latitudes, has a significant impact on the ASM system. The monsoon onset over the Bay of Bengal (BOB), a consequence of the air-sea interaction, is modulated by forcing related to TP physical characteristics and the land-sea thermal contrast over south Asia during the spring season (Wu et al. 2011). Wu and Zhang (1998) demonstrated that thermal and mechanical forcing by the TP favors the ASM onset that occurs first over the BOB, which was first proposed in the early 1980s (Ananthakrishnan et al. 1983) and confirmed by more recent studies (e.g. Lau and Yang 1996; Mao et al. 2011; Wu et al. 2011; Wu and Zhang 1998).

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The monsoon system over the TP is governed by complex processes. The vast cryosphere, which in total is the largest ice mass outside the Arctic and Antarctica, also serves as a reservoir for both water and energy which interacts with the ASM circulation. Xie et al. (2005) described a negative correlation between TP snow cover and the subsequent East Asian Summer Monsoon as determined by western North Pacific typhoon frequency and the number of typhoon landfalls in China. Changes in the snow cover, along with changes in surface albedo and thereby sensible heating, also modulate the atmospheric circulation over the TP (Wu and Kirtman 2007; Xu et al. 2009). Monsoon variability has been characterized using various methods, including the all Indian summer rainfall index based on the Indian Meteorological Department stations (e.g., Parthasarathy et al. 1992), physical proxies based on reanalysis data [e.g., time-mean zonal wind shear (Webster and Yang 1992), meridional wind shear (Goswami et al. 1999), area averaged negative OLR anomalies (Wang and Fan 1999), tropospheric temperature gradient (Xavier et al. 2007) and meridional temperature gradient (Mao et al. 2011)], and theoretical models for atmospheric general circulation (e.g., Lau and Yang 1996). However, it should be noted that monsoon variation may not be the sole determinant of precipitation intensity, as the increase in atmospheric moisture in a warmer climate would also affect the frequency of precipitation events, even if atmospheric circulation remains the same (Trenberth 2011). Thus the identification of monsoon variability by precipitation distribution and intensity might be supplemented by physical processes analysis associated with monsoon circulation. Many investigators have attempted to understand ASM variability using that methodology (Goswami and Jayavelu 2001; Wang et al. 2004a, b; Webster and Yang 1992).

Stable isotopic ratios are highly influenced by atmospheric physical processes and are widely used to reconstruct atmospheric circulation (Liu et al. 2008; Yao et al. 2013). Since 1961 the Global Network of Isotopes in Precipitation has yielded valuable data which have enhanced our understanding of the effects of meteorological parameters (precipitation, temperature, air circulation) and atmospheric kinetics on stable isotopic ratios (Araguas-Araguas et al. 2000; Dansgaard 1964; Sengupta and Sarkar 2006). In addition, a network of stations has been established across the TP (the Tibetan Network for Isotopes in Precipitation, or TNIP) to obtain samples from precipitation events for stable isotope analysis and to take measurements related to atmospheric circulation (Yao et al. 2013). These data have been used to delineate the northern limit of monsoon intrusion on the TP (Tian et al. 2001) and to categorize the three major atmospheric circulation domains (Yao et al. 2013).

Determining the timing of the monsoon onset is important as it is essential for agricultural and societal development. The Coupled Model Intercomparison Project Phase 5 projects a weakening of the Indian summer monsoon circulation in an increasingly warm climate, which is nevertheless accompanied by increasing precipitation that is largely attributed to increased atmospheric moisture content (Trenberth 2011; IPCC 2013). Multiple indices to characterize the monsoon that incorporate various atmospheric circulation features have been proposed, yet a well-defined or widely accepted index remains elusive (Wang et al. 2004a, b). The isotopic composition of precipitation has the potential to provide an alternative means to address this issue, since such data contain information on the atmospheric processes associated with precipitation.

Data from TNIP have been used to identify temporal monsoon variations, i.e., an earlier summer monsoon onset over the Bay of Bengal than over the South China Sea (Yang et al. 2012b).Here we discuss new results that build on that study, using ground observations that are essential for verifying the performance of model simulations which provide credible explanations of physical mechanisms of monsoon processes and help improve projections of future scenarios (IPCC 2013). Our primary objectives are to address the onset timing of the Asian monsoon sub-systems in this region over the last decade using the oxygen isotopic values of precipitation ($\delta^{18}O_p$), and to verify the characteristic isotopic signals of monsoon variations by considering multiple atmospheric and oceanic impacts on $\delta^{18}O_p$. We use $\delta^{18}O_p$ data from samples collected daily from 2007 to 2014 to investigate monsoon variability, which is verified using reanalysis data. We discuss factors affecting $\delta^{18}O_p$ and explore the role of those factors in the isotopic signal of the monsoon initiation.

2 Sampling and data processing

For event precipitation sampling at Lulang (LL) and Nuxia (NX) in the southeastern TP, and at Guangzhou (GZ) on the southeastern coast of China (Fig. 1), we received cooperation from the local meteorological stations at NX and GZ and the Chinese Academy of Sciences' field station in the southeastern TP (Table 1). All these stations are manned in shifts around the clock to ensure continuous operation of manual and automatic equipment. Because of the high relative humidity and the necessity for high sampling frequency during summer months, the sampling procedure included the use of deep buckets with plastic bag inserts at all collection points. Samples were collected immediately after each event and poured into 15 ml polyethylene bottles which were tightly capped before being placed in cold storage at the stations. Note that each precipitation event yielded only one bottle of sample that was filled as much as possible. Snow samples were allowed to melt at room temperature before being poured into bottles. The humid environment, immediate collection and cold storage facilities ensured minimal