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# Spatial-seasonal patterns reveal large-scale atmospheric controls on Asian Monsoon precipitation water isotope ratios

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ABSTRACT

Correlated seasonal variation in precipitation amount and its oxygen isotope ratios ($\delta^{18}$O) has long been observed and frequently invoked in the interpretation of paleo-$\delta^{18}$O records from the Asian Monsoon (AM) region. However, the underlying cause of the observed seasonal $\delta^{18}$O variation is still under debate. Precipitation $\delta^{18}$O values show a single, consistent seasonal pattern across the region, with high values in pre-monsoon (late-spring to early-summer) and low values in the monsoon mature (mid- to late-summer) periods. We tested three hypotheses that may give rise to the measured precipitation $\delta^{18}$O pattern, involving variation in: 1) local precipitation, 2) moisture sources, and 3) convection in moisture source regions. We show that seasonal precipitation amounts across the AM region exhibit two pattern types: pre-monsoon peak or monsoon mature peak, and thus do not provide a consistent explanation for the isotopic pattern. We test the hypotheses that changing moisture sources or moisture source isotope ratios drive the seasonal isotopic pattern using a combination of Lagrangian moisture source attribution and output from an isotope-enabled General Circulation Model (LMDZ4), but find little seasonal variation in moisture sources; that which does exist is not consistent with the observed isotopic change. Instead, we show that the precipitation $\delta^{18}$O transition from pre-monsoon to monsoon mature stage is correlated with intensification of convective activity in moisture source regions, which is the result of monsoon establishment and northward migration of the Intertropical Convergence Zone (ITCZ). We propose that light water vapor, transferred to the lower-troposphere through downdrafts and evaporation of rain in the vicinity of intense convection, is advected to the AM region and labels precipitation during the monsoon mature period. These results demonstrate that precipitation $\delta^{18}$O in the AM region more strongly reflect large-scale atmospheric dynamics than local precipitation amount or moisture source, guiding the interpretation of paleo-isotope data from this region.

## 1. Introduction

Monsoon regions are characterized by strong seasonal reversal in atmospheric circulation and associated wet/dry alternation. The Asian Monsoon (AM) is the archetypal monsoon system (Wang, 2006). In the region it affects human wellbeing, which is intimately linked to water resources, natural disasters such as heavy rainfalls and droughts, and other weather phenomena. Thus, understanding the dynamics and variability of the AM is of great scientific and socioeconomic importance.

Precipitation isotope signals ($\delta$D and $\delta^{18}$O, both in modern precipitation and reconstructed from proxy archives), which vary in response to climatic system processes (e.g., Araguás-Araguás et al., 1998; Bowen and Wilkinson, 2002; Dansgaard, 1964; Rozanski et al., 1993), have proven valuable in understanding present monsoon climate and providing opportunities to study the history of the monsoon as far back as 640,000 yr ago (e.g., Cheng et al., 2016; Thompson et al., 2000; Wang et al., 2001; Yao et al., 2013). The "amount effect" (the inverse correlation between monthly precipitation $\delta^{18}$O and precipitation amount) (Dansgaard, 1964) is

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a prominent empirical relationship derived from modern isotopic studies in tropical and monsoon regions. The amount effect has been documented and studied in the AM region, where it can be observed as anti-phase seasonal variations in precipitation amount and precipitation $\delta^{18}$O values at some (e.g., Araguás-Araguás et al., 1998; Yao et al., 2013), but not all sites (e.g., Breitenbach et al., 2010; Tang et al., 2015), and has been adopted in the interpretation of many paleoclimate records in the region (e.g., Tan et al., 2018; Tian et al., 2003).

There is now a strong consensus that the empirical amount effect is not mechanistically associated with variation in local precipitation amount, but rather reflects large-scale atmospheric phenomena. Researchers studying the AM region have explored three different types of explanations for the amount effect observed in this region. First, some work has continued to focus on the traditional association of precipitation $\delta^{18}$O with local precipitation amount, which presumably reflects the extent of rainout and associated isotopic fractionation in different systems. This negative relationship has remained of particular interest in paleoclimate studies, where researchers seek to reconstruct local precipitation at sites where proxy records were obtained (e.g., Dayem et al., 2010; Tan et al., 2018).

Second, as early as 1989, scientists found a sharp decrease in snowfall $\delta^{18}$O values on the Tibetan Plateau during the monsoon onset (from late May to early June) and attributed this transition to changes in moisture sources, with high values associated with continental moisture and low values with oceanic moisture (Yao et al., 1991). A later regional study also attributed seasonal variation in AM precipitation $\delta^{18}$O to seasonally changing moisture sources (Araguás-Araguás et al., 1998), and this moisture source hypothesis has been widely advanced to explain precipitation isotope patterns in the AM region (e.g., Breitenbach et al., 2010; Peng et al., 2010; Tang et al., 2015; Xie et al., 2011). Robust support for and mechanistic understanding of this hypothesis remains elusive, however, and it is not clear whether there is actually a large shift in moisture sources during the monsoon season or whether varying vapor source $\delta^{18}$O values can explain the precipitation isotope observations. A recent moisture source study in the East AM region, for example, showed that despite strong westerly water vapor transport in winter the majority of moisture contributing to precipitation came from the tropical oceans (Li et al., 2016).

A third set of hypotheses for the AM amount effect focuses on upstream atmospheric processes, such as convective intensity and moisture convergence. Convective processes have the potential to alter local precipitation and vapor isotope compositions in the source regions (Kurita, 2013; Lee et al., 2007; Moore et al., 2014; Risi et al., 2008a; Worden et al., 2007), and the propagation of this vapor to downstream sites could influence precipitation isotope ratios in the AM region (Cai and Tian, 2016a; He et al., 2015; Tang et al., 2015). These processes have been shown to affect precipitation isotope ratios at short timescales (event to interannual scales) in the AM region (e.g., Cai et al., 2017; Tang et al., 2015) and other monsoon regions (e.g., Risi et al., 2008b; Vimeux et al., 2005). For instance, Tang et al. (2015) suggested that the combined effects of source region location and upstream rainout cause intra-seasonal precipitation $\delta^{18}$O variation at Nanjing during the summer monsoon. Cai and Tian (2016a) suggested that seasonal variation in East AM precipitation $\delta^{18}$O values is related to cloud-top height variation associated with monsoon convective intensity, raising questions about the significance of moisture source as a control on regional precipitation isotope ratios.

These uncertainties in our understanding of modern precipitation $\delta^{18}$O variations (the amount effect and controlling mechanisms), in part, hinder the interpretation of paleo-$\delta^{18}$O records from natural archives, such as ice cores from the Tibetan Plateau (e.g., Thompson et al., 2000), speleothems from southeast China (e.g., Liu et al., 2015), and tree ring cellulose (e.g., Xu et al., 2015). For example, whether speleothem $\delta^{18}$O records from southeast China are robust proxies for East AM precipitation amount or not remains an open discussion (e.g., Dayem et al., 2010; Liu et al., 2015; Tan et al., 2018). As new paleo-$\delta^{18}$O records are developed at a growing rate and new technology allows resolution of sub-annual paleo-$\delta^{18}$O records in this region (e.g., Xu et al., 2015), a clearer understanding of modern precipitation $\delta^{18}$O variation is becoming more important and urgent.

Here we spatially characterize seasonal variations in precipitation amount and precipitation $\delta^{18}$O from station data and gridded data products to examine the amount effect across the AM region. Based on the results we identify two distinct seasonal precipitation patterns in the region, one dominant in areas of southeast China where precipitation peaks before the summer monsoon onset, and one characteristic of much of the rest of the region with maximum precipitation during the mature stage of the summer monsoon. Focusing on the region dominated by the pre-monsoon maximum, we conduct daily back trajectory calculation over ten years to determine moisture sources during these two seasons and infer moisture source isotopic composition using an isotope-enabled General Circulation Model (LMDZ4). To test whether results from this subregion are applicable to the broader AM region, we conduct a comparative study on a sub-region of the monsoon mature domain in south Asia. Our results suggest that moisture source variation does not offer a consistent explanation for precipitation isotope variation within both monsoon sub-regions, and we propose instead that this variation is driven by upstream convective processes that isotopically deplete lower-troposphere vapor within vapor source regions. Seasonal variation in precipitation $\delta^{18}$O is thus controlled largely by source region convection and associated large-scale atmospheric circulation.

## 2. Data and methods

### 2.1. Isotope and climate data

Our work uses precipitation $\delta^{18}$O observations from several sources to obtain data from across the AM region. These data include event-based precipitation $\delta^{18}$O data at Lhasa, southern Tibetan Plateau from 1993–2014 (Cai et al., 2017) and at Lulang, southeast Tibetan Plateau from 2007–2014 (Yang et al., 2017); event-based precipitation $\delta^{18}$O data at Guangzhou, southeast China from 2007–2009 (Xie et al., 2011); and monthly precipitation $\delta^{18}$O from Global Network of Isotopes in Precipitation (GNIP) stations in the AM region (https://nucleus.iaea.org/wiser). Associated precipitation amount data from the isotope monitoring stations are also used in this work. For the event-based data, we calculated precipitation-amount weighted monthly mean $\delta^{18}$O values. GNIP data are also available for the Lhasa and Guangzhou stations, but with different temporal coverage from the event-based data. In these cases both data sources were combined to achieve longer temporal coverage. Many GNIP stations have temporal gaps in their records. Here we used only those stations with adequate data to estimate long-term monthly mean values for all 12 months (section 3). In most cases, these long-term monthly mean values represent multi-year average, with a few exceptions in winter months due to sparse precipitation. We note that some of these stations only have data coverage of several years. However, temporal variability of precipitation $\delta^{18}$O at annual and longer timescales is much smaller than seasonal variability. Therefore, we argue that the temporally short data coverage at these stations will only have a small impact on the estimated seasonal $\delta^{18}$O variability. One station, Sylhet, was excluded from the analyses in section 3 given that data for December were not available, but provided an adequate monthly record to be used in section 4.4.