Effects of changes in moisture source and the upstream rainout on stable isotopes in precipitation — a case study in Nanjing, East China

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Abstract. In the Asian monsoon region, variations in the stable isotopic composition of speleothems have often been attributed to the "amount effect". However, an increasing number of studies suggest that the "amount effect" in local precipitation is insignificant or even non-existent. To explore this issue further, we examined the variability of daily stable isotopic composition ($\delta^{18}O$) in precipitation from September 2011 to November 2014 in Nanjing, East China. We found that $\delta^{18}O$ in summer precipitation was not significantly correlated with local rainfall amount, but could be linked to changes in the location and rainout processes of precipitation source regions. Our findings suggest that the stable isotopes in summer precipitation could signal the location shift of precipitation source regions in the inter-tropical convergence zone (ITCZ) over the course of the monsoon season. As a result, changes in moisture source location and upstream rainout effect should be taken into account when interpreting the stable isotopic composition of speleothems in the Asian monsoon region. In addition, the temperature effect on isotopic variations in non-monsoonal precipitation should be

also involved because precipitation in the non-monsoon season accounts for about half of its annual precipitation.

1 Introduction

The “amount effect” refers to the observed negative correlation between the isotopic composition in precipitation and rainfall amount. It was first put forward by Dansgaard (1964), and is generally observed in low-latitude regions (Araguás-Araguás et al., 1998). Based on this relationship, stable isotopic records obtained from low-latitude regions are often used for paleohydroclimate reconstructions (Cruz et al., 2005, 2009; Partin et al., 2007; Tierney et al., 2008; Sano et al., 2012). However, some recent studies suggest that the “amount effect” is insignificant or even non-existent in low-latitude monsoon areas. For example, Conroy et al. (2013) found spatial and temporal examples of precipitation–isotope mismatches across the tropical Pacific, indicating that factors beyond the “amount effect” influence precipitation isotope variability. They compared 12 isotope-equipped global climate models to assess the distribution of simulated stable isotopic variability. Model simulations support observations in the western tropical Pacific, showing that monthly $\delta^{18}O$ are correlated with large-scale, not local, precipitation (Conroy et al., 2013). Peng et al. (2010) also found no significant correlation between precipitation amount and $\delta^{18}O$ values in the western Pacific monsoon region near Taiwan. They suggest that moisture sources of diverse air masses with different isotopic signals are the main factor controlling the precipitation isotopic characteristics. Breitenbach et al. (2010) observed no empirical amount effect at their study site in the monsoonal northeast India. They identified a strong trend towards lighter isotope values over the course of the summer monsoon, with lowest $\delta^{18}O$ and δD values in late monsoon season, with a temporal offset between the highest rainfall and the most negative $\delta^{18}O$. Other observations (Lawrence et al., 2004; Kurita et al., 2009) show that at marine island stations, even short-term (daily or event-based) isotopic variations are independent of local precipitation intensity, but linked to the rainout process in the surrounding regions. Some ice core studies also suggest that records of precipitation $\delta^{18}O$ in ice cores of the Indian monsoon region do not match the local precipitation amount. For example, Pang et al. (2014) found a significant correlation between $\delta^{18}O$ records from the East Rongbuk ice cores and summer monsoon rainfall along the southern slope of the Himalayas, whereas no significant correlation was found between the $\delta^{18}O$ records and accumulation rates (an indicator of local precipitation). This suggests that summer monsoon precipitation $\delta^{18}O$ over the high Himalayas is controlled by the upstream rainout over the entire southern slope of the Himalayas rather than local precipitation processes.

Stable oxygen isotopes in speleothems are widely used for paleoclimate reconstructions. Recently, stable oxygen isotopes measured in cave speleothems from China have received much attention: e.g., Hulu Cave (Wang et al., 2001), Dongge Cave (Yuan et al., 2004; Dykoski et al., 2005; Kelly et al., 2006), Sanbao Cave (Wang et al., 2008; Cheng et al., 2009), Heshang Cave (Hu et al., 2008), Wanxiang Cave (Zhang et al., 2008), Buddha Cave (Paulsen et al., 2003), and Dayu Cave (Tan et al., 2009) (Fig. 1). However, the interpretation of these stable isotope records in speleothems remains controversial. Some researchers used the stable isotope records from stalagmites in monsoonal east China as proxies for precipitation amount (Hu et al., 2008; Tan et al., 2009; Cai et al., 2010). Paulsen et al. (2003) showed that short-term (<10 years) variations in $\delta^{18}O$ in stalagmites from Buddha Cave reflect changes in precipitation amounts, but longer-term

(>50 years) $\delta^{18}O$ variations indicate changes in air temperature. Other studies suggest that $\delta^{18}O$ indicates changes in the ratio of summer to winter precipitation, which they refer to as "monsoon intensity" (Wang et al., 2001; Yuan et al., 2004; Dykoski et al., 2005; Kelly et al., 2006; Wang et al., 2008; Zhang et al., 2008; Cheng et al., 2009). Dayem et al. (2010) reported that annual and rainy season precipitation totals in each of central China, south China, and east India have correlation length scales of ~500 km, shorter than the distance between many speleothem records that share similar long-term time variations in $\delta^{18}O$ values. Thus, the short correlation distances do not support the idea that apparently synchronous variations in $\delta^{18}O$ values at widely spaced (>500 km) caves in China are due to variations in annual precipitation amounts. Most of the above-mentioned studies indicate that the variations of $\delta^{18}O$ in speleothems from the Asian summer monsoon region are not controlled by the local precipitation amount.

Recent studies have revealed the importance of variability in moisture sources (Peng et al., 2010; Xie et al., 2011) and large-scale convective activities (Vimeux et al., 2011; Tremoy et al., 2012; Kurita, 2013; Moerman et al., 2013; Lekshmy et al., 2014; He et al., 2015) in controlling precipitation $\delta^{18}O$ in monsoon regions. Strong convection at source regions tends to produce more precipitation, causing heavy isotopes to preferentially condense from vapor, leading to lower values of downstream precipitation $\delta^{18}O$. In addition, the location of moisture source determines the distance that water vapor has to travel, hence affects the precipitation $\delta^{18}O$. Soderberg et al. (2013) found that the variability of the isotopic composition of individual rain events in central Kenya could be partly explained by the distance traveled of air mass over land. Therefore, the rainout effect at the water vapor source areas and upstream regions should have a significant influence on stable isotopes in precipitation in downstream regions (Vuille et al., 2005).

In the Asian monsoon regions, moisture sources for summer precipitation often lie in the strong convection areas within the inter-tropical convergence zone (ITCZ). The variability of ITCZ position and intensity could therefore affect precipitation $\delta^{18}O$ in these regions. Using the outgoing longwave radiation (hereafter OLR) as a tracer for deep tropical convection (Wang et al., 1997), the ITCZ position and strength could be identified (Gu and Zhang, 2002). In the East Asia–West Pacific region, the onset of the Asian summer monsoon corresponds to the northward movement of the ITCZ to an area between 5°–25°N (Ding, 2007), and brings with it large amount of convective precipitation (Ananthakrishnan et al., 1981). In this study, we examined in detail how summer precipitation $\delta^{18}O$ related to changes in the position and intensity of moisture sources within ITCZ, using the daily $\delta^{18}O$ data at Nanjing in summer (June–September) during 2012–2014, the daily OLR data, and relevant meteorological data. The daily OLR data are from the NCEP reanalysis data, provided by the NOAA/ORA/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd. According to long term monthly means of Nanjing precipitation for the years 1981-2010 from the China Meteorological Data Sharing Service System (http://cdc.nmic.cn/home.do), summer precipitation (June-September) accounts for 54.8% of its annual precipitation, indicating that the non-monsoonal precipitation (45.2%) (October-May) is also important. Therefore, factors controlling the isotopic variations in the non-monsoonal precipitation were also discussed, aiming for improving the interpretation of the oxygen isotopic records in speleothems in the Asian monsoon region.

2 Study area

2.1 General atmospheric circulation

Nanjing is located on the lower reaches of the Yangtze River, surrounded by low hilly terrain with an average altitude of 26 m (Fig. 1a). The mean annual air temperature is 16°C and the average annual precipitation is 1106 mm. Located close to the Tropic of Cancer, this area has a strong seasonal climate (Fig. 1b), with a distinct seasonal reversal of wind and alternation of dry and rainy periods. In the winter, the air masses over Nanjing mainly originate from the high pressure system over Mongolia in the North and West (Fig. 1a). In the summer, the city is under the influence of both the East Asian summer monsoon and the Indian summer monsoon (Fig. 1a).

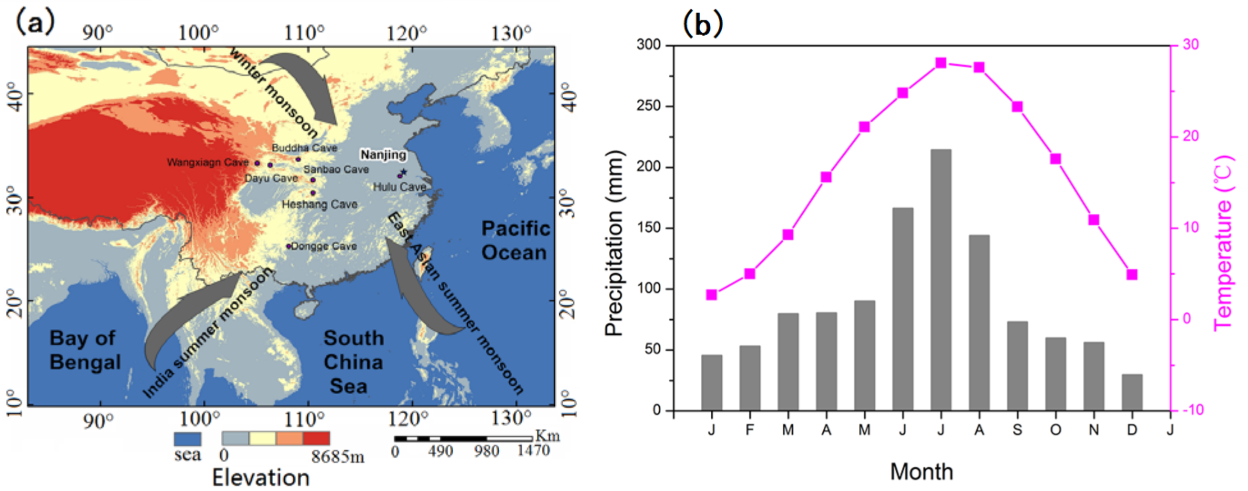


Fig. 1. (a) Elevation map of China; the study site Nanjing is marked by a black star. Black dots indicate the cave locations mentioned in this study: Hulu, Dongge, Heshang, Sanbao, Wanxiang, Buddha, and Dayu. Grey arrows indicate the dominant circulation patterns over the region. (b) Monthly average temperature (T) and monthly average precipitation (P) for the years 1981–2010; data from the China Meteorological Data Sharing Service System.

2.2 Intraseasonal variations in the Asian Summer Monsoon

With the onset of the summer monsoon, the warm and moist air masses from the south collide with cold northerly air masses in east China, forming a quasi-stationary rain belt known as Meiyu. The weather systems developed at the Meiyu front provide the majority of summer precipitation in this region, with the enhanced moisture transport from the South China Sea and the Bay of Bengal (Ding, 1992). The Meiyu system also includes the Baiu in Japan (Saito, 1995) and the Changma in Korea (Oh et al., 1997). Meiyu starts in southern China between April and May, moving to the middle part of eastern China (Yangtze and Huai He River Basins) in May and July, and to northern China in July and August, bringing with it consistent rainfall. Baiu occurs from mid-June to mid-July in Japan (Saito, 1995), and Changma takes place from the end of June to the end of July when the rain belt shifts northward to Korea (Oh et al., 1997). The retreat of the Asian summer monsoon is observed earliest in East Asia, and occurs very rapidly, taking only a month or less to retreat from northern to southern China. In early September, the leading edge of the summer monsoon quickly withdraws southward to the northern part of the South China Sea and remains there, marking the end of the summer monsoon in East Asia (Ding, 1992; Ding, 2007).

2.3 Moisture sources of summer precipitation

To determine the probable source regions of the air masses influencing our study area, we generated backward trajectories based on the Hybrid Single-Particle Lagrangian Integrated Trajectories (HYSPLIT) of the Air Resources Laboratory of the US National Oceanic and Atmospheric Administration, based on the data generated by the Global Data Assimilation System (GDAS) (ftp://arlftp.arlhq.noaa.gov/pub/archives/gdas1). Although backward trajectory analysis only reflects the synoptic situation and is only an approximation of the general origin of an air mass, this approach has been widely used in studies of moisture transport (Brimelow et al., 2005; Perry et al., 2007; Sodemann et al., 2009; Drumond et al., 2011). In our study, the vapor source trajectory was simulated for each summer precipitation event from June to September, and cluster analysis was applied to the trajectories. The moisture transport paths were identified using the HYSPLIT back trajectory model combined with NCEP reanalysis at 12-h time steps back to 11 d at 1500 m AGL (above ground level) (about 850 hPa), as water vapor transport is usually concentrated in the middle and lower troposphere (Bershaw et al., 2012). The total spatial variance (TSV) (Fig. 2a) was used to identify the optimum number of clusters. Rapid growth in TSV occurred when the number of clusters fell below six, therefore six clusters were retained as the final simulated cluster trajectories.

The simulation suggests that in summer, Nanjing was dominated by the influence of several major moisture sources: the Bay of Bengal, the South China Sea, the western Pacific, and the northern inland areas (Fig. 2b).

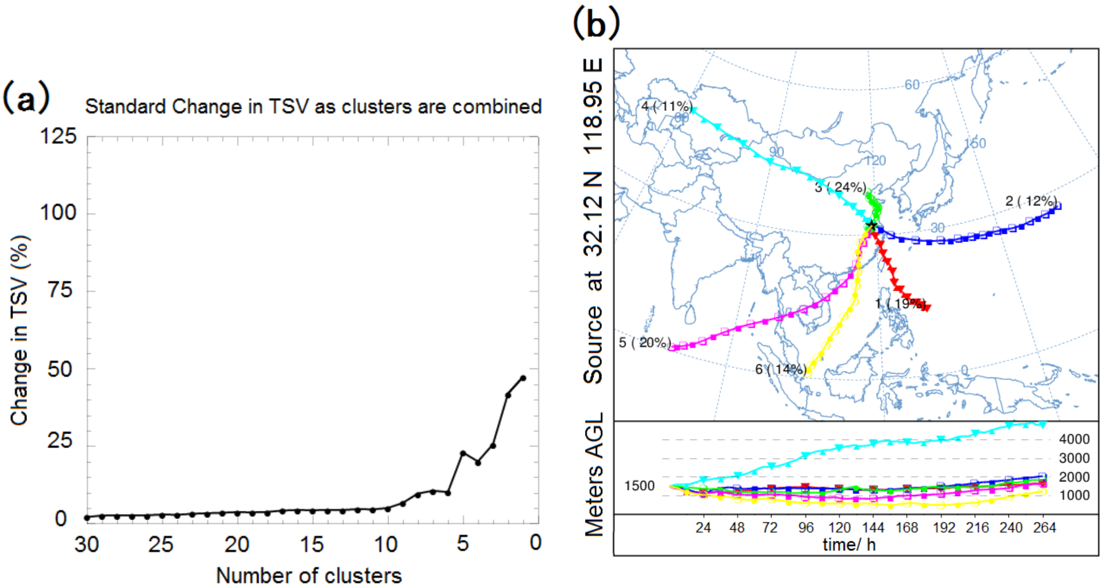


Fig. 2. (a) Change in TSV (total spatial variance) as clusters are combined, and (b) Spatial distribution of water vapor pathways. The percentage shows the frequency of each clustered

backward trajectory in summer season.

2.4 Moisture sources of non-monsoonal precipitation

The vapor source trajectory for each non-monsoonal precipitation event from October to May was also simulated by the HYSPLIT model using the same method used for summer precipitation. The moisture transport paths back to 7d at 500 m AGL were determined by the model because of the stronger wind speed and relatively lower height of precipitation condensation in the non-monsoon season. The simulated trajectories are presented in Fig. 3. The simulation suggests that in the non-monsoon season, Nanjing was dominated by two major moisture sources: the remote inland of the Eurasia and the China offshore seas (the Yellow Sea and the Bohai Sea) (Fig. 3).

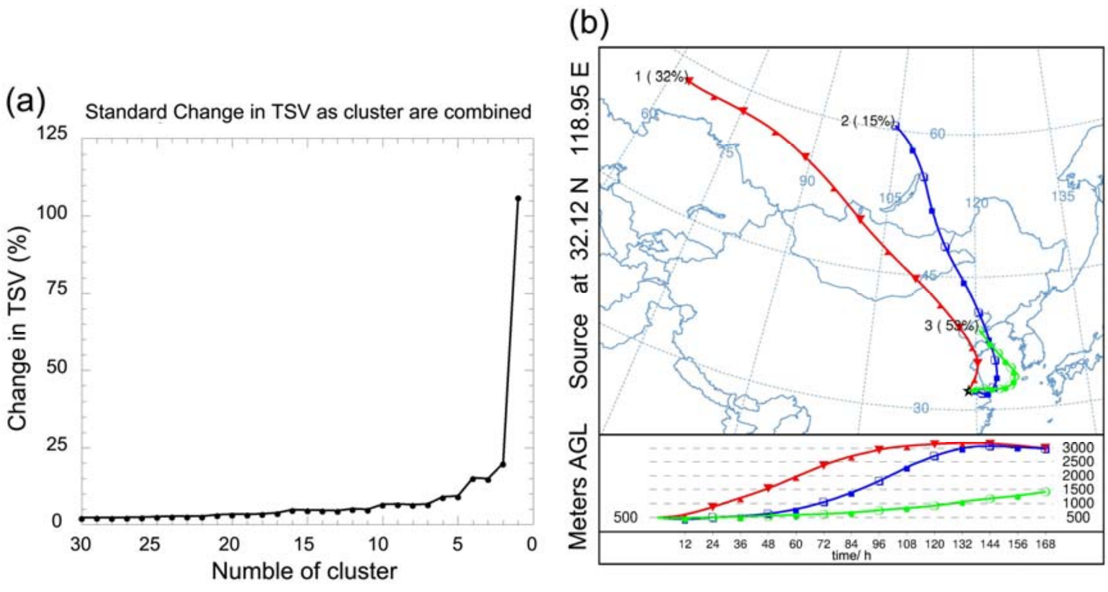


Fig. 3. (a) Change in TSV (total spatial variance) as clusters are combined, and (b) Spatial distribution of water vapor pathways. The percentage shows the frequency of each clustered backward trajectory in the non-monsoon season.

3 Sampling and isotope measurements

Using a deep open-mouthed container, precipitation samples were collected on days with precipitation greater than 0.1 mm from September 2011 to November 2014 with the exception of January-April 2013. Immediately after collection, the samples were poured into 100 mL polyethylene bottles and sealed tightly for storage in a freezer.

The $\delta^{18}O$ and δD of these samples were simultaneously measured using a Picarro L2120-i wavelength scanned-cavity ring down spectroscopy (WS-CRDS) system at the Key Laboratory of Coast and Island Development of the Ministry of Education, School of Geographic and Oceanographic Sciences, Nanjing University, China.

The stable isotopic ratio was calculated as:

$$\delta = \left[\frac{R_{\text{sample}}}{R_{\text{reference}}} - 1 \right] \times 1000\text{‰}$$

where R is the ratio of the composition of the heavier to lighter isotopes in water ($^{18}O/^{16}O$ for $\delta^{18}O$, or D/H for δD), and the reference is the Vienna Standard Mean Ocean Water standard. Each sample was measured eight times. The first five measurements were discarded in order to eliminate the effect of memory. The average of the last three measurements was calibrated based on the linear regression between the known isotopic values of our three internal water standards and their measured values. The calibrated values of samples were taken as the test results. The analytical uncertainty is less than 0.1‰ for $\delta^{18}O$ and 0.5‰ for δD. A quadratic error for d-excess is less than 1.0‰, estimated by the uncertainties of $\delta^{18}O$ and δD.

4 Results

4.1 Seasonal variations of stable isotopes in precipitation

Temporal variations of daily precipitation stable isotopes ($\delta^{18}O$, δD and d-excess), precipitation amount, and surface air temperature in Nanjing during the observation period are presented in Fig. 4. The isotopic data exhibits significant seasonal variations, with low values of the $\delta^{18}O$, δD and d-excess in the summer monsoon season and high values in the non-monsoon season. In detail, the $\delta^{18}O$ values in the summer monsoon season (the non-monsoon season) vary from -14.8‰ to -1.5‰ (-9.5‰ to 2.3‰), from -106.0‰ to -0.3‰ (-59.0‰ to 26.2‰) for δD, and from -1.4‰ to 24.8‰ (-1.3‰ to 28.1‰) for d-excess. The mean weighted-precipitation $\delta^{18}O$ in the summer monsoon season (the non-monsoon season) is -9.1‰ (-4.9‰), –61.8‰ (-23.4‰) for δD, and 10.9‰ (15.5‰) for d-excess.

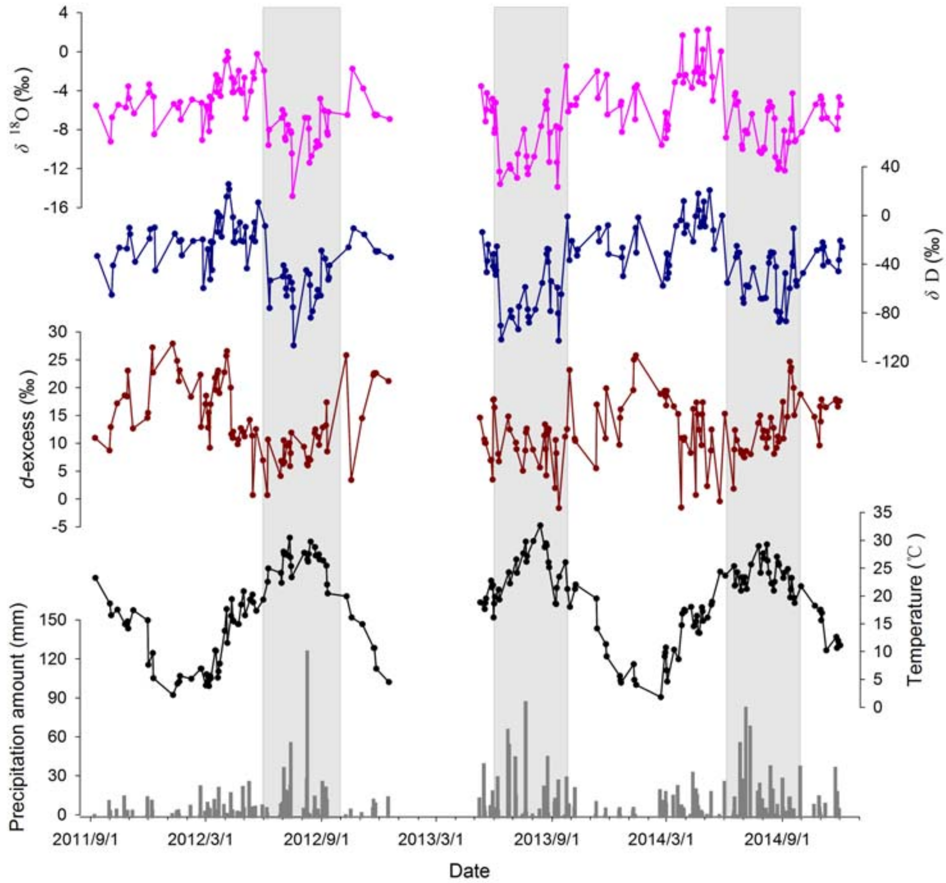


Fig. 4. Temporal variations of daily precipitation $\delta^{18}O$, δD, d-excess, precipitation amount, and surface air temperature in Nanjing from September 2011 to November 2014. The shaded bars

represent the summer monsoon seasons (June to September). Note the missing data from January to April 2013. The daily precipitation amount and surface air temperature data were from the China Meteorological Data Sharing Service System.

4.2 δ^{18}O variations in summer precipitation

In 2012, after a sudden decrease on June 6, the precipitation δ^{18}O remained low, reaching a minimum (-14.8‰) on July 14. The δ^{18}O values increased in early August, and decreased again in late August. In early September, δ^{18}O in precipitation became enriched (Fig. 5b). In 2013, precipitation δ^{18}O decreased suddenly on June 7, then increased slowly until it peaked (-4.0‰) on August 22. The stable isotope composition was depleted in late August and reached a minimum (-13.8‰) on September 7. In late September, δ^{18}O in precipitation was enriched (Fig. 5c). In 2014, δ^{18}O in precipitation decreased on June 1 and slightly increased afterward until it was depleted again in July. It started to increase in early August. From late August to early September, δ^{18}O in precipitation remained depleted, but became enriched since late September (Fig. 5d).

We divided the summer into 5 distinct stages (Figure 5), based on the temporal patterns δ^{18}O variations, together with the intraseasonal variations in the Asian summer monsoon and Meiyu (see section 2.2). Stage 1 started with the sudden decrease in δ^{18}O in early June, which is generally considered as an indicator for the onset of the summer monsoon (e.g., Tian et al., 2001; Vuille et al., 2005; Yang et al., 2012). Stage 2 covered the Meiyu period. The start dates of Meiyu in 2012–2014 were June 26, June 23, and June 25 respectively, based on the observations by the Jiangsu Provincial Meteorological Bureau. Stage 3 was characterized by relatively high precipitation $\delta^{18}O$, whereas in stage 4, $\delta^{18}O$ remained low. Stage 5 marked the return of $\delta^{18}O$ values to enriched state. The 5 stages were delineated in Figure 5(b)-(d).

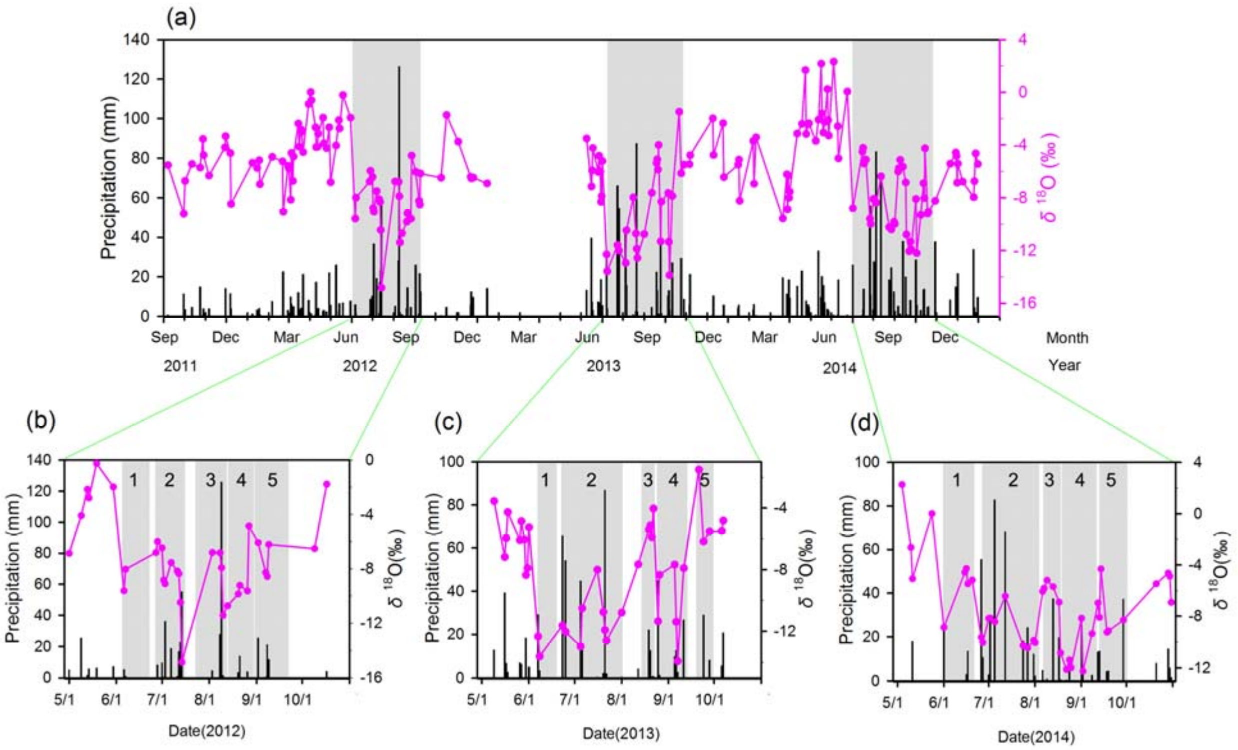


Fig. 5. (a) Temporal variation of daily precipitation $\delta^{18}O$ and precipitation amount (P) from September 2011 to November 2014. The daily precipitation data were from the China Meteorological Data Sharing Service System. Note the missing data for $\delta^{18}O$ from January to April 2013. (b)–(d): Temporal variations in daily precipitation $\delta^{18}O$ and local precipitation amount from May to October in 2012 (b), 2013 (c), 2014 (d). The shaded bars represent different stages.

In (b) for 2012, stage 1: June 3 - June 20; stage 2: June 27 - July 14; stage 3: July 20 - August 9; stage 4: August 10 - August 26; and stage 5: August 27 - September 20.

In (c) for 2013, stage 1: June 7 - June 20; stage 2: June 23 - August 1; stage 3: August 12 - August 22; stage 4: August 25 - September 11; and stage 5: September 20 - September 30.

In (d) for 2014, stage 1: June 1 - June 20; stage 2: June 26 - August 1; stage 3: August 6 - August

17; stage 4: August 18 - September 8; and stage 5: September 12 - September 30.

4.3 The amount effect of δ^{18}O in summer precipitation

The amount effect refers to the observed negative correlation between precipitation isotopic composition and precipitation amount (Dansgarrd, 1964). The most discussed mechanism for the amount effect is that high precipitation rates increase relative humidity, hence decrease evaporation. As evaporation serves to enrich heavy isotopes, its reduction leads to more depleted precipitation isotopic signatures. Moreover, high relative humidity also inhibits re-evaporation of local surface water (lakes and streams) to feed back into the precipitation. As local surface water is usually more enriched in heavy isotopes, its diminished input also leads to more depleted precipitation isotopic composition. Here we investigated if the amount effect could be clearly observed from our data. We performed separate correlation analyses between precipitation δ^{18}O and precipitation amount, relative humidity and the evaporation ratio defined as evaporation divided by precipitation (E/P) (Fig. 6). There was a weak negative correlation between precipitation δ^{18}O and precipitation amount in 2013 (Fig. 6b). In addition, precipitation δ^{18}O became more depleted with increased relative humidity (Fig. 6e) and decreased evaporation/precipitation ratio (Fig. 6h). This seems to suggest that the amount effect was present in the 2013 data. However, no significant correlation was observed in 2012 and 2014 (Fig. 6a, c).

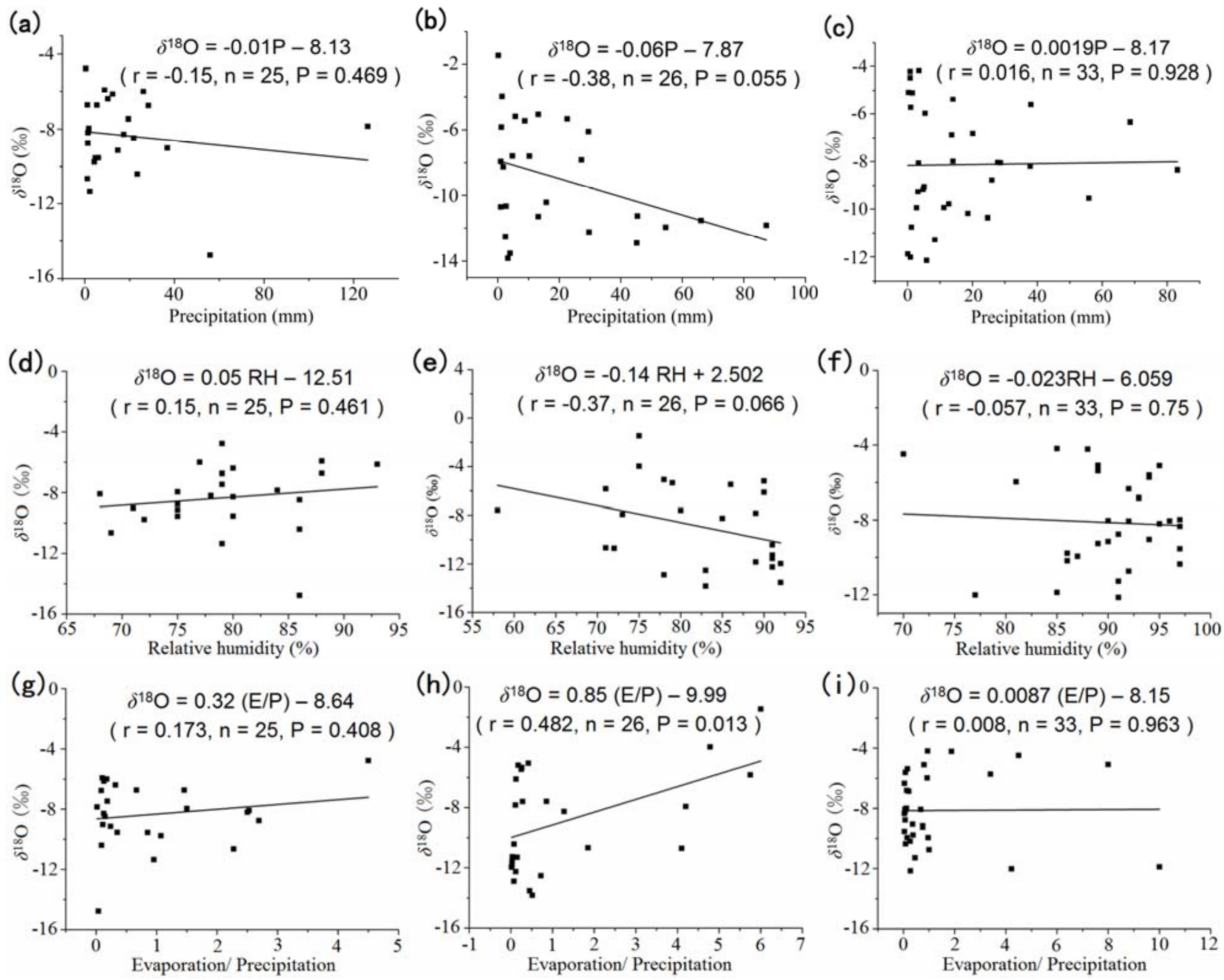


Fig. 6. This figure shows: (1) correlation between δ^{18}O and precipitation amount in Nanjing from June to September for 2012 (a), 2013 (b) and 2014 (c); (2) correlation between δ^{18}O and relative humidity in Nanjing from June to September for 2012 (d), 2013 (e) and 2014 (f); (3) correlation between δ^{18}O and evaporation/precipitation in Nanjing from June to September for 2012 (g), 2013 (h) and 2014 (i). Linear regression lines, correlation coefficient r and p-values are also shown.

4.4 The temperature effect of δ^{18}O in non-monsoonal precipitation

Although the temperature effect of stable isotopes in precipitation in southeast Asia is often damped or even reverse due to the summer monsoon influence (Araguas-Araguas et al., 1998), the temperature effect generally exists in the non-monsoonal season due to the winter monsoon influence. As expected, the daily precipitation δ^{18}O was positively correlated with surface air temperature in the non-monsoon seasons of the observation period, with a linear T-δ^{18}O relationship: $\delta^{18}O = 0.16\,T - 6.56$ (Fig. 7).

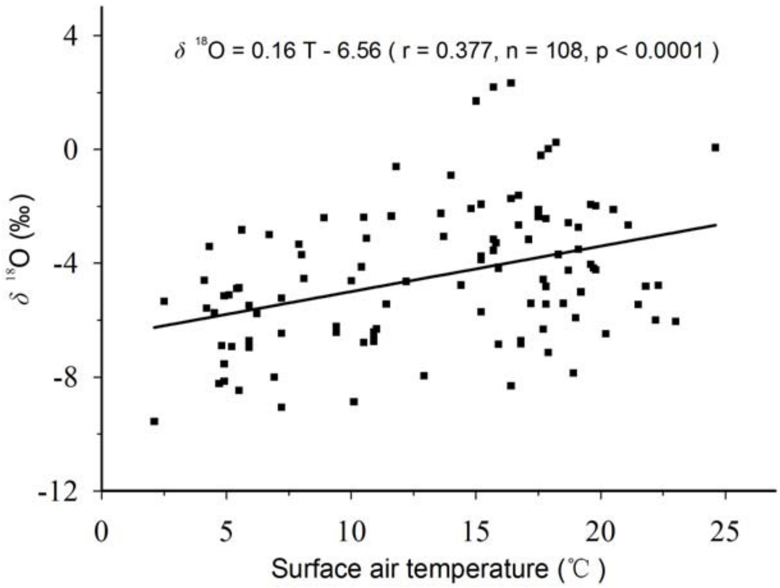


Fig. 7. Correlation between daily precipitation δ^{18}O and surface air temperature (T) in Nanjing in the non-monsoon seasons of the observation period.

5 Discussion

The ITCZ region is an important moisture source for precipitation in general, and for monsoon precipitation in particular. Therefore, the monsoon is often considered as a manifestation of the intraseasonal migration of the ITCZ (Gadgil, 2003). To explore the possible influence of ITCZ intensity and position on δ^{18}O in summer precipitation in Nanjing, a composite analysis of OLR was performed for each stage (Fig. 8). Low OLR values correspond to cold and high clouds associated with enhanced convection, and a negative relationship is generally observed between OLR and convection intensity (Wang et al., 1997). Therefore, a composite analysis of OLR could help establish the location and intensity of deep convections associated with ITCZ, which serve as moisture sources for the monsoon precipitation in Nanjing. It was also necessary to establish the moisture transport for each stage in order to link the source regions with our study area and determine the distance, as both could potentially influence the precipitation δ^{18}O. To achieve this, we calculated the vertically integrated mean water vapor transport for each stage, using the daily NCEP/NCAR reanalysis data (Fig. 9). This was calculated as the horizontal wind field (zonal and meridional winds) multiplied by specific humidity, which was then integrated from surface to 300 hPa level.

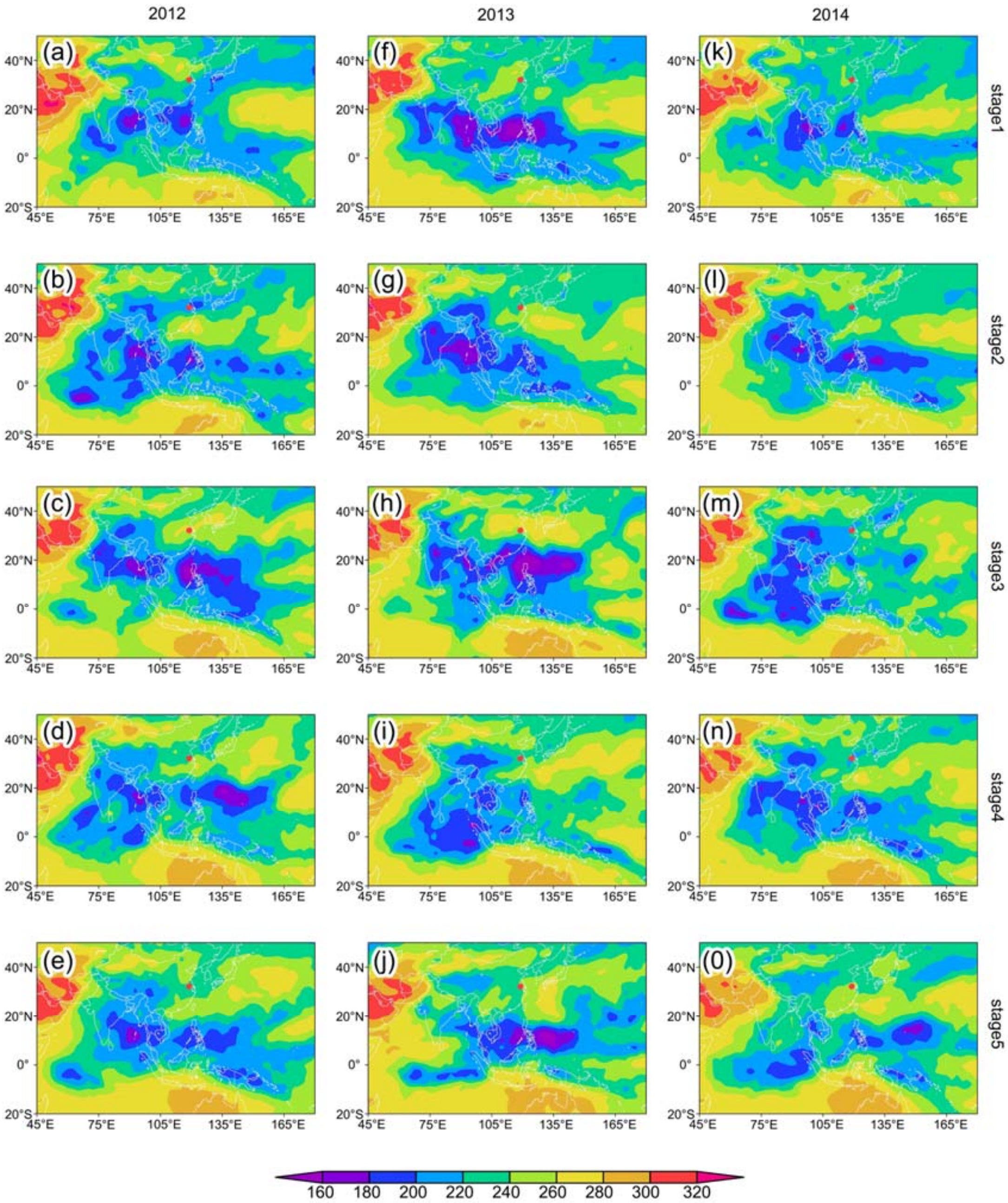


Fig. 8. Composite results for average OLR (W m^{-2}) for stages 1 to 5. The convective activity is indicated by low values in OLR. Daily OLR data at 2.5° × 2.5° resolution were used (http://www.esrl.noaa.gov/psd). The study site of Nanjing is marked by a red dot. (a)–(e): stages 1 to 5 in 2012; (f)–(j): stages 1 to 5 in 2013; (k)–(o): stages 1 to 5 in 2014.

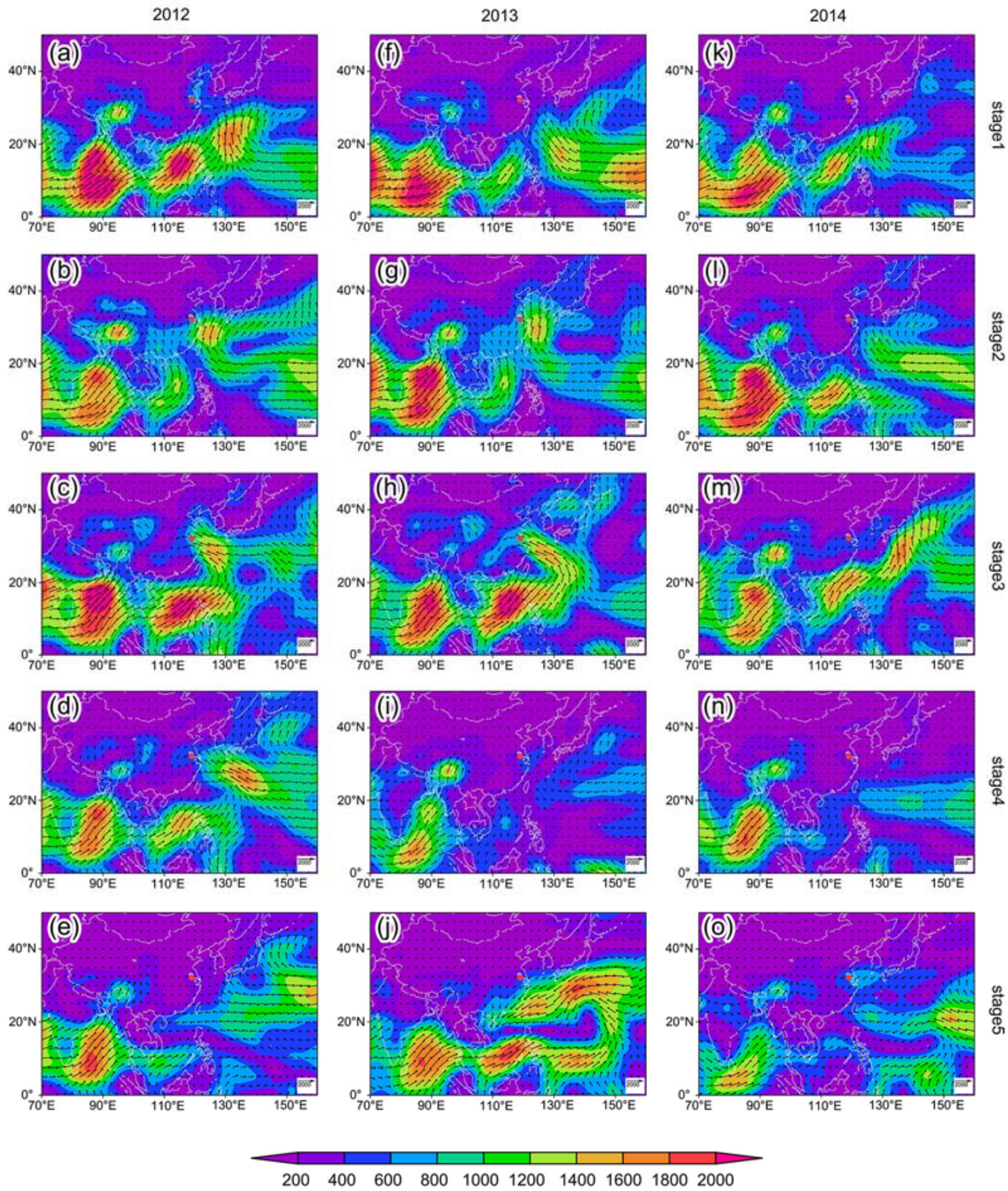


Fig. 9. Vertically integrated mean water vapor transport (g cm^{-1} s^{-1}). Different colors indicate the magnitude of the moisture flux vector. The study site of Nanjing is marked by a red dot. (a)–(e) standing for stages 1 to 5 in 2012; (f)–(j) for stages 1 to 5 in 2013; (k)–(o) for stages 1 to 5 in 2014.

In stage 1, the abrupt decrease of δ^{18}O indicated the onset of the Asian summer monsoon, with strong ITCZ convections in the Bay of Bengal and the South China Sea (Fig. 8a, f, k), and the delivery of moisture from both regions (Fig. 9a, f, k). The isotope fractionation that occurred during the strong convection and the transport process lightened the stable isotopes in water vapor, resulting in the abrupt decrease of $\delta^{18}O$ in precipitation in Nanjing.

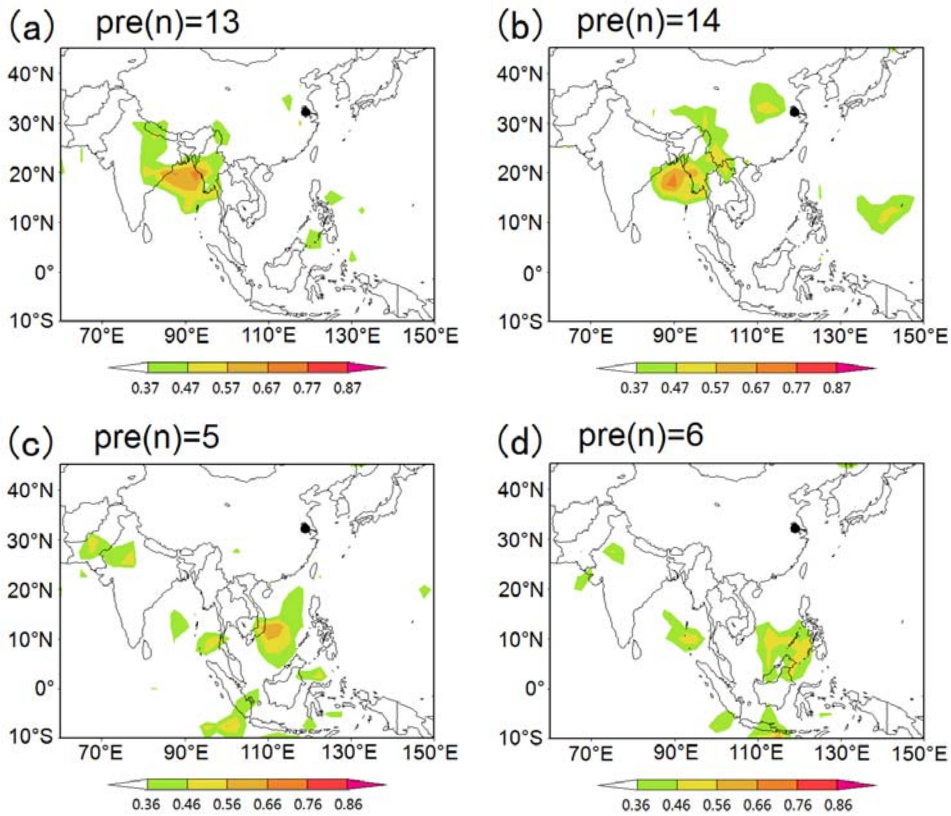
In stage 2, the ITCZ intensity and location in 2012 did not change significantly from stage 1 (Fig. 8b), and $\delta^{18}O$ remained low. The extreme negative $\delta^{18}O$ on July 14 was due to the continuous local rainfall from July 12 to 14, further depleting $\delta^{18}O$ in precipitation. In 2013, the ITCZ intensity did not change much in the Bay of Bengal, but decreased significantly in the South China Sea and the low-latitude western Pacific Ocean (Fig. 8g). Weak convection reduced the rainout effect, and hence increased $\delta^{18}O$ in precipitation. In 2014 the ITCZ intensity increased in the South China Sea and the low-latitude western Pacific Ocean, but it did not change significantly in the Bay of Bengal (Fig. 8l). At this stage, as the meridional water vapor transport to the north from the South China Sea increased (Fig. 9b, g, l), changes in convective activity in the South China Sea had a stronger influence on $\delta^{18}O$ in study area precipitation. Strong convection in the South China Sea enhanced rainout effect, resulting in depleted $\delta^{18}O$ in precipitation in Nanjing.

In stage 3, the ITCZ intensity decreased in the Bay of Bengal in both 2012 and 2013, but increased in the South China Sea and the low-latitude western Pacific Ocean. The center of strong convection propagated northward (Fig. 8c, h). Water vapor mainly originated from the South China Sea and the low-latitude western Pacific Ocean (Fig. 9c, h) for this stage. The relatively shorter transport distance resulted in higher $\delta^{18}O$ values in precipitation. In 2014, the ITCZ intensity was relatively low in the South China Sea and the low-latitude western Pacific Ocean (Fig. 8m). The water vapor came mainly from the adjacent seas (Fig. 8m). As a result, the relatively weak convection in the area and short transport distance enriched $\delta^{18}O$ in precipitation in Nanjing.

Stage 4 covered the late monsoon season. In 2012, in addition to increased convection strength in the west Pacific Ocean, the strong convective center also moved eastward, increasing the water transport distance to Nanjing. Both of these changes acted to deplete $\delta^{18}O$ in precipitation. Moreover, the moisture transport suggested that vapor from the Bay of Bengal was also transported to Nanjing (Fig. 9d). The strong convection in the Bay of Bengal and its long distance from the study site contributed to further deplete $\delta^{18}O$ in precipitation. In 2013 and 2014, the ITCZ intensity in the South China Sea and the western Pacific was relatively weak. However, both the moisture transport from the Bay of Bengal (Fig. 9i, n) and the convective activity in the Bay of Bengal was strong (Fig. 8i, n). In addition, the strong convective center in the Bay of Bengal moves southward in stage 4 of 2013 (Fig. 8i) resulting in longer distance from Nanjing. The combination of these factors depleted the isotopic composition of precipitation in this stage for both 2013 and 2014. The time series of $\delta^{18}O$ in precipitation showed a clear trend of decreasing $\delta^{18}O$-values during the late monsoon period, while rainfall peaked earlier in the season. The depleted $\delta^{18}O$ values in late monsoon season were also observed in the other monsoon areas. Pang et al. (2006) suggested that the low $\delta^{18}O$ values were caused by the recycling of monsoon precipitation in late monsoon season. Breitenbach et al. (2010), on the other hand, argued that the Bay of Bengal freshwater plume, consisted of isotopically depleted rain water and snow melt water, diluted the Bay of Bengal surface water $\delta^{18}O$ pool in late monsoon season. This contributed to the depleted $\delta^{18}O$ in precipitation. Our results suggest that the depleted precipitation $\delta^{18}O$ in the late monsoon season could result from the combination of increased convective activities and transport distance due to the retreat of the ITCZ southward in the Bay of Bengal.

In stage 5, the Asian summer monsoon retreated and water vapor from the inland areas with a high stable isotopic composition was transported to Nanjing (Fig. 9e, j, o), enriching the $\delta^{18}O$ in precipitation. It is worth noting that the ITCZ intensity in the South China Sea and the low-latitude western Pacific Ocean strengthened in stage 5 of 2013 because of the super Typhoon Usagi. However, Nanjing was no affected due to its location at the edge of the Typhoon. At the time, the moisture in Nanjing came mainly from the northern inland areas and the adjacent seas in the northeast (Fig. 9e, j, o). Therefore, the stable isotopic composition of precipitation remained enriched.

The above observations seemed to suggest a close relationship between precipitation $\delta^{18}O$ and the convective activity in the moisture source regions. In order to further explore this relationship quantitatively, we performed a time-lagged spatial correlation analysis between precipitation $\delta^{18}O$ in Nanjing and the daily OLR time series. Results are shown in Fig. 10. Several patterns emerged from this analysis. For stage 1 and 4, there was a strongest positive correlation between $\delta^{18}O$ and OLR in the Bay of Bengal at 13 and 14 days before the rainfall (Fig. 10a, b). This supports the conclusion of previous studies that convective processes could have integrated impacts on water vapor over several days preceding precipitation events (Tremoy et al., 2012; Gao et al., 2013). For stage 2, our analysis showed a strongest positive correlation between $\delta^{18}O$ and the OLR in the South China Sea at 5 and 6 days preceding the rainfall (Fig. 10c, d). This confirms the significant influence of convective intensity in the South China Sea on $\delta^{18}O$ in precipitation in Nanjing at stage 2. As this stage covered the Meiyu period, this result is largely in agreement with previous studies, which indicate that moisture for Meiyu precipitation mainly comes from the South China Sea (Simmonds et al., 1999; Ding et al., 2007). For stage 5, the strongest positive correlation was observed between daily δ^{18}O in precipitation and OLR in the inland areas to the north and west at 7 and 8 days before the rainfall (Fig. 10e, f), suggesting that inland vapor contributed to δ^{18}O in precipitation after the monsoon withdrew. However, no significant correlation between δ^{18}O and OLR was found for stage 3. This could partially attributed to the shift of ITCZ location northward and eastward in 2012 and 2013 (Fig. 8c, h), reducing the vapor transport distance (Fig. 9c, h). This could have played a more important role in determining the δ^{18}O values in precipitation in Nanjing than convective intensity.



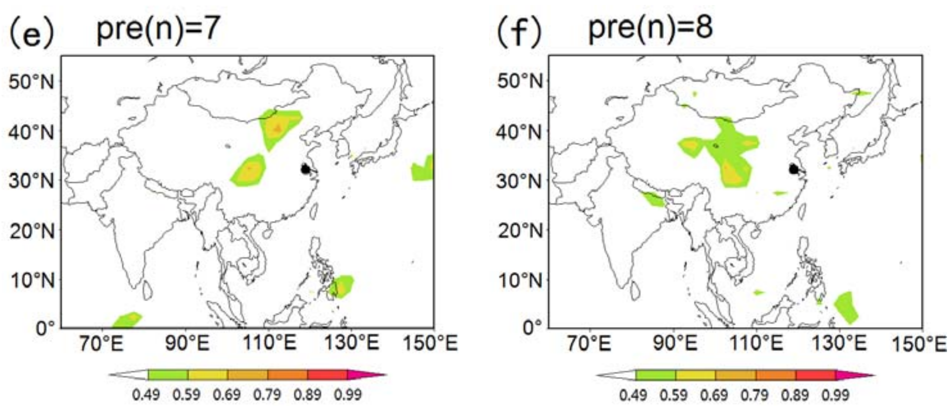


Fig. 10. Spatial correlation between daily δ^{18}O in precipitation and OLR at *n* days prior to the rainfall date: Spatial correlation between δ^{18}O in precipitation and OLR at 13 days (a) and 14 days (b) prior to the rainfall date for stages 1 and 4; Spatial correlation between δ^{18}O in precipitation and OLR at 5 days (c) and 6 days (d) prior to the rainfall date for stage 2; Spatial correlation between δ^{18}O in precipitation and OLR at 7 days (e) and 8 days (f) prior to the rainfall date for stage 5. For all maps, only areas with correlations significant at 0.05 level are shown. The study site Nanjing is marked with a black dot.

Our results suggest that the upstream convective activity over the tropical regions of the Bay of Bengal, the South China Sea and the western Pacific has an important impact on the isotopic composition of summer precipitation in Nanjing. Strong distillation processes during intense convective activity would increase the rainout of heavy isotopes upstream, hence deplete the isotopic composition in precipitation downstream, and vice versa. Therefore, the isotopic composition in summer precipitation downstream of the moisture sources in the tropics could be determined mainly by changes of the isotopic composition of atmospheric vapor in the upstream source region rather than the precipitation amount on site. Pausata et al. (2011) used a climate model with an embedded oxygen-isotope model to simulate a Heinrich event and found that the variations of stalagmite $\delta^{18}O$ values in southern China mainly reflected $\delta^{18}O$ changes in the source vapor from the Indian Ocean rather than local precipitation amount. Liu et al. (2015) also indicated that the stalagmite $\delta^{18}O$ records during the Holocene from the East Asian summer monsoon region are essentially a signal of the isotopic composition of precipitation, which is largely determined by the upstream depletion mechanism over the Indian Ocean and the Indian monsoon region.

As a result, the upstream rainout effect associated with the convective processes over the moisture source region is likely an important factor that affects the isotopic variability in the Asian summer monsoon precipitation. However, a correlation between the $\delta^{18}O$ and precipitation amount in the summer of 2013 (Fig. 6b) seemed to suggest that the amount effect could still play an important role, particularly during the periods when precipitation varied greatly such as the glacial-interglacial climate cycles. In addition, there is likely considerable amount of local evapotranspiration in the Asian monsoon region because of high vegetation cover under humid monsoon climate conditions. How the local evapotranspiration affects the summer precipitation $\delta^{18}O$ is still unclear and requires further study.

The linear slope (0.16‰/℃) between the daily surface air temperature and $\delta^{18}O$ in non-monsoonal precipitation is consistent with the slope (0.20‰/℃) calculated by the monthly isotopic and air temperature data of Nanjing during the non-monsoon season obtained from the Global Network for Isotopes in Precipitation (GNIP) at http://isohis.iaea.org/gnip.asp. This confirms the temperature effect of stable isotopes in the non-monsoon season. By contrast, the correlation between surface air temperature and non-monsoonal precipitation $\delta^{18}O$ of Nanjing is weaker than the correlation in high latitudes. This may be caused by changes in moisture source of the remote moisture deriving from the inland of Eurasia versus the proximal moisture originating in the China offshore seas (Fig. 3). In addition, the effect of potential re-evaporation of precipitation on isotopic composition of precipitation during its falling due to relatively dry climate condition in the non-monsoon season could also contribute to the weak temperature effect of stable isotopes. Anyhow, the considerable precipitation amount in the non-monsoon season highlights the importance of the temperature effect for interpretation of stable isotope records in speleothems from the monsoon region. Some studies demonstrated that winter temperature in East China was dominated by the East Asian winter monsoon associated with the Mongolia High (Guo, 1994; Liu et al., 2011).

As a result, the isotopic composition of precipitation, which was preserved in stable oxygen isotope records from speleothems in the East Asian monsoon region, should be controlled by both the East Asian summer monsoon and the East Asian winter monsoon. Indeed, Clemens et al. (2010) suggested that the timing of light $\delta^{18}O$ peaks in speleothems from Southeast China at the orbital time scale were controlled by both strong summer monsoons and winter temperature changes. Other studies suggest that the oxygen isotope records in Chinese speleothems indicate changes in the ratio of summer to winter precipitation (Wang et al., 2001; Yuan et al., 2004; Dykoski et al., 2005; Kelly et al., 2006; Wang et al., 2008; Zhang et al., 2008; Cheng et al., 2009). However, this inference lacks theoretical basis because influencing factors on stable isotopes of precipitation were not taken into account. Indeed, there was no correlation between the annual mean weighted-precipitation $\delta^{18}O$ and the ratio of summer to winter precipitation based on modern observations of precipitation stable isotopes data from GNIP Nanjing station and our study (figure not shown, the year with lack observation more than two months was not included for statistical analysis).

In summary, for improving the interpretation of the oxygen isotopic records in speleothems in the Asian monsoon region at longer time scales such as the glacial-interglacial climate cycles, the upstream rainout on stable isotopes related to changes of the Asian summer monsoon and the temperature effect associated with winter monsoon should be considered, which could be evaluated by present-day and past simulations of water stable isotopes in the general circulation models (Risi et al., 2010; Werner et al., 2011).

6 Conclusions

We emphatically analyzed daily stable isotopic composition of summer precipitation in Nanjing in 2012–2014, and related it to OLR and water vapor transport data to identify the influence of ITCZ location and intensity on the stable isotopic composition of precipitation. At the onset of the summer monsoon (stage 1), vapor to our study site was mainly transported from the Bay of Bengal, where the strong convection in the source area and its relatively long distance from our study area acted to reduce $\delta^{18}O$ in precipitation in Nanjing. During the Meiyu period (stage 2), water vapor came mainly from the South China Sea, and changes in ITCZ intensity in the South China Sea led to the variability of $\delta^{18}O$ in precipitation in Nanjing. The northward propagation of the ITCZ during the mid-monsoon season (stage 3) reduced the vapor transport distance, resulting in relatively enriched $\delta^{18}O$. During the late monsoon period (stage 4), the ITCZ retreated to the Bay of Bengal. The strong convection and relatively long-distance vapor transport again led to depleted $\delta^{18}O$ values in precipitation in Nanjing. Finally, when the monsoon withdrew (stage 5), vapor from the north and west inland areas contributed to the enriched δ^{18}O.

Our study indicates that the changes in the ITCZ location and intensity are major factors affecting the stable isotopes in summer precipitation in Nanjing. Therefore, the stable isotopes in precipitation could signal a shift of precipitation source regions and ITCZ over the course of monsoon season. As a result, changes in moisture sources and upstream rainout effect should be taken into account when interpreting the stable isotopic composition of speleothems in the Asian monsoon region. However, the temperature effect of stable isotopes is also important for interpreting the stable isotopic composition of speleothems in the Asian monsoon region because of almost half annual precipitation occurring in the non-monsoon season.

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References:

Ananthakrishnan, R., Pathan, J. M., and Aralikatti, S. S.: On the northward advance of the ITCZ and the onset of the southwest monsoon rains over the southeast Bay of Bengal, Int. J. Climatol., 1,153-165, 1981.

Araguas-Araguas, L., Froehlich, K., and Rozanski, K.: Stable isotope composition of precipitation over southeast Asia, J. Geophys. Res., 103(D22), 28721-28742, 1998.

Araguás-Araguás, L., Froehlich, K., and Rozanski, K.: Stable isotope composition of precipitation over Southeast Asia, J. Geophys. Res., 103, D22, 721-28742, 1998.

Bershaw, J., Penny, S. M., and Garzione, C. N.: Stable isotopes of modern water across the Himalaya and eastern Tibetan Plateau: implications for estimates of paleoelevation and paleoclimate, J. Geophys. Res., 117: D02110, doi:10.1029/2011JD016132, 2012.

Breitenbach, S. F. M., Adkins, J. F., Meyer, H., Marwan, N., Kumar, K. K., and Haug, G. H.: Strong influence of water vapor source dynamics on stable isotopes in precipitation observed in Southern Meghalaya, NE India, Earth. Planet. Sci. Lett., 292, 212-220, 2010.

Brimelow, J. C. and Reuter, G. W.: Transport of atmospheric moisture during three extreme rainfall events over the Mackenzie River basin, J. Hydrometeorol., 6, 423-440, 2005.

Cai, Y. J., Tan, L. C., Cheng, H., An, Z. S. Edwards, R. L., Kelly, M. J., Kong, X. G., and Wang, X. F.: The variation of summer monsoon precipitation in central China since the last deglaciation, Earth Planet. Sci. Lett., 291, 21-31, 2010.

Cheng, H., Edwards, R. L., Broecker, W. S., Denton, G. H., Kong, X. G., Wang, Y. J., Zhang, R., and Wang, X. F.: Ice Age Terminations, Science, 326, 248-252, 2009.

Clemens, S. C., Prell, W. L., and Sun, Y.: Orbital-scale timing and mechanisms driving Late Pleistocene Indo-Asian summer monsoons: Reinterpreting cave speleothem $\delta^{18}O$, Paleoceanography, 25, PA4207, doi:10.1029/2010PA001926, 2010.

Conroy, J. L., Cobb, K. M., and Noone, D.: Comparison of precipitation isotope variability across the tropical Pacific in observations and SWING2 model simulations, J. Geophys. Res., 118, 5867-5892, 2013.

Cruz, F. W., Burns, S. J., Karmann, I., Sharp, W. D., Vuille, M., Cardoso, A. O., Ferrari, J. A., Dias, P. L. S., and Viana, O. Jr.: Insolation-driven changes in atmospheric circulation over the past 116000 years in subtropical Brazil, Nature, 434, 63-66, 2005.

Cruz, F. W., Vuille, M., Burns, S. J., Wang, X. F., Cheng, H., Werner, M., Edwards, R. L., Karmann, Ivo., Auler, A. S., and Nguyen, H.: Orbitally driven east-west antiphasing of South American precipitation, Nature Geoscience, 2, 210-214, 2009.

Dansgarrd, W.: Stable isotopes in precipitation, Tellus, 16, 436-468, 1964.

Dayem, K. E., Molnar, P., Battisti, D. S., and Roe, G. H.: Lessons learned from oxygen isotopes in modern precipitation applied to interpretation of speleothem records of paleoclimate from eastern Asia, Earth Planet. Sci. Lett., 295, 219-230, 2010.

Ding, Y. H., Liu, J. J., Sun, Y., Liu, Y. J., He, J. H., and Song. Y. F.: A Study of the Synoptic-Climatology of the Meiyu System in East Asia, Chinese Journal of Atmospheric Sciences (in Chinese), 31, 1082-1100, 2007.

Ding, Y. H.: Summer monsoon rainfall in China, J. Meteor. Soc. Japan, 70, 373-396, 1992.

Ding, Y. H.: The variability of the Asian summer monsoon, J. Meteor. Soc. Japan, 85B, 29, 2007.

Drumond, A., Nieto, R., Gimeno, L.: On the contribution of the tropical western hemisphere warm pool source of moisture to the Northern Hemisphere precipitation through a Lagrangian approach, J. Geophys. Res., 16, D00Q04, doi:10.1029/2010JD15397, 2011.

Dykoski, C. A., Edwards, R. L., Cheng, H., Yuan, D. X., Cai, Y. J., Zhang, M. L., Lin, Y. S., Qing, J. M., An, Z. S., and Revenaugh, J.: A high-resolution, absolute-dated Holocene and deglacial Asian monsoon record from Dongge Cave, China, Earth Planet. Sci. Lett., 233, 71-86, 2005.

Gadgil, S.: The Indian monsoon and its variability, Annu. Rev. Earth Planet. Sci., 31, 429-467, 2003.

Gao, J., Delmotte, V. M., Risi, C., He, Y., and Yao, T. D.: What controls precipitation $\delta^{18}O$ in the southern Tibetan Plateau at seasonal and intra-seasonal scales? A case study at Lhasa and Nyalam, Tellus, 65: 1-14, 2013.

Gu, G. J., and Zhang, C. D.: Cloud components of the Intertropical Convergence Zone, J. Geophys. Res., 107(D21), 4565, doi:10.1029/2002JD002089, 2002.

Guo, Q.: Relationship between the variations of East Asian winter monsoon and temperature anomalies in China, Quarterly Journal of Applied Meteorology, 5(2), 218-225, 1994 (in Chinese with English abstract).

He, Y., Risi, C., Gao, J., Masson-Delmotte, V., Yao, T., Lai, C., Ding, Y., Worden, J., Frankenberg, C., Chepfer, H., and Cesana, G.: Impact of atmospheric convection on south Tibet summer precipitation isotopologue composition using a combination of in situ measurements, satellite data, and atmospheric general circulation modeling, J. Geophys. Res. Atmos., 120, 3852-3871, doi:10.1002/2014JD022180, 2015.

Hu, C. Y., Henderson, G. M., Huang, J. H., Xie, S. C., Sun, Y., and Johnson, K. R.: Quantification of Holocene Asian monsoon rainfall from spatially separated cave records, Earth Planet. Sci. Lett., 266, 221-232, 2008.

Kelly, M. J., Edwards, R. L., Cheng, H., Yuan, D. X., Cai, Y. J., Zhang, M. L., Lin, Y. S., and An, Z. S.: High resolution characterization of the Asian Monsoon between 146,000 and 99,000 years B.P. from Dongge Cave, China and global correlation of events surrounding Termination Ⅱ, Palaeogeogr. Palaeoclimatol. Palaeoecol., 236, 20-38, 2006.

Kurita, N., Ichiyanagi, K., Matsumoto, J., Yamanaka, M. D., and Ohata, T.: The relationship between the isotopic content of precipitation and the precipitation amount in tropical regions. J. Geochem. Explor., 102, 113-122. 2009.

Kurita, N.: Origin of Arctic water vapor during the ice-growing season, Geophys. Res. Lett., 38, L02709, doi:10.1029/2010GL046064, 2011.

Kurita, N.: Water isotopic variability in response to mesoscale convective system over the tropical ocean, J. Geophys. Res., 118, 10376-10390, 2013.

Lau, K. M. and Yang, S.: Climotology and interannual variability of the Southeast Asian summer monsoon, Adv. Atmos. Sci., 14, 141-162, 1997.

Lau, K. M., Kim, and Yang, S.: Dynamical and boundary forcing characteristics of regional components of the Asian summer monsoon, J. Climate., 13, 2461-2482, 2000.

Lawrence, J. R. and Gedzelman, S. D.: Low stable isotope ratios of tropical cyclone rains, Geophys. Res. Lett., 23, 527-530, 1996.

Lawrence, J. R., Gedzelman, S. D., Dexheimer, D., Cho, H. K., Carrie, G. D., Gasparini, R., Anderson, C. R., Bowman, K. P., and Biggerstaff, M. I.: Stable isotopic composition of water vapor in the tropics, J. Geophys. Res., 109, D06115, doi:10.1029/2003JD004046,2004.

Lekshmy, P. R., Midhum, M., Ramesh, R., and Jani, R. A.: ^{18}O depletion in monsoon rain relates to large scale organized convection rather than the amount of rainfall, Scientific Reports, 4, 5661, doi:10.1038/srep05661, 2014

Liu, J., Chen, J., Zhang, X., Li, Y., Rao, Z., and Chen, F.: Holocene East Asian summer monsoon records in northern China and their inconsistency with Chinese stalagmite δ^{18}O records, Earth-Science Reviews, 148, 194-208, 2015.

Liu, Q., Wang, P., Xu, X., Zhi, H., and Sun, X.: A group of circulation indices of Mongolia High and analysis of its relationship with simultaneous anomaly in the climate of China, Journal of Tropical Meteorology, 27(6), 889-898, 2011 (in Chinese with English abstract).

Moerman, J. W., Cobb, K. M., Adkins, J. F., Sodemann, H., Clark, B., and Tuen, A. A.: Diurnal to interannual rainfall variations in northern Borneo driven by regional hydrology, Earth. Planet. Sci. Lett., 369, 108-119, 2013.

Oh, T. H., Kwon, W. T., and Ryoo, S. B.: Review of the researches on Changma and future observational study (KORMEX), Adv. Atmos. Sci., 14, 207-222, 1997.

Pang, H. X., He, Y. Q., Lu, A. G., Zhao, J. D., Ning, B. Y., Yuan, L. L., and Song, B.: Synoptic-scale variation of $\delta^{18}O$ in summer monsoon rainfall at Lijiang, China, Chin. Sci. Bull., 51, 2897-2904, 2006.

Pang, H., Hou, S., Kaspari, S., and Mayewski, P. A.: Influence of regional precipitation patterns on stable isotopes in ice cores from the central Himalayas, The Cryosphere, 8, 289-301, 2014.

Partin, J. W., Cobb, K. M., Adkins, J. F., Clark, B., and Fernandez, D. P.: Millennial-scale trends in west Pacific warm pool hydrology since the Last Glacial Maximum, Nature, 449, 452-455, 2007.

Paulsen, D. E., Li, H. C., and Ku, T. L.: Climate variability in central China over the last 1270 years revealed by high-resolution stalagmite records, Quaten. Sci. Rev., 22, 691-701, 2003.

Pausata, F. S., Battisti, D. S., Nisancioglu, K. H., Bitz, C. M., 2011. Chinese stalagmite $\delta^{18}O$ controlled by changes in the Indian monsoon during a simulated Heinrich event. Nat. Geosci. 4, 474-480.

Peng, T. R., Wang, C. H., Huang, C. C., Fei, L. Y., Chen, C. T. A., and Hwong, J. L.: Stable isotopic characteristic of Taiwan's precipitation: A case study of western Pacific monsoon region, Earth Planet. Sci. Lett., 289, 357-366, 2010.

Perry, L. B., Konrad, C. E., Schmidlin, T. W.: Antecedent upstream air trajectories associated with northwest flow snowfall in the southern Appalachians, Wea. Forecasting, 22, 334-351, 2007.

Qian, W. H. and Lee, D. K.: Seasonal march of Asian summer monsoon, Int. J. Climatol., 20, 1371-1381, 2000.

Risi, C., Bony, S., Vimeux, F., and Jouzel, J.: Water-stable isotopes in the LMDZ4 general circulation model: Model evaluation for present-day and past climates and applications to climatic interpretations of tropical isotopic records, J. Geophy. Res., 115, D12118, doi:10.1029/2009JD013255.

Saito, N.: Quasi-stationary waves in mid-latitudes and Baiu in Japan, J. Meteor. Soc. Japan, 63, 983-995, 1995.

Sano, M., Xu, C. X., and Nakatsuka, T.: A 300-year Vietnam hydroclimate and ENSO variability record reconstructed from tree ring $\delta^{18}O$, J. Geophys. Res., 117, D12115, doi:10.1029/2012JD017749, 2012.

Simmonds, I., Bi, D., and Hope, P.: Atmospheric water vapor flux and its association with rainfall over China in summer, J. Climate., 12, 1353-1367, 1999

Sodemann, H., Stohl, A.: Asymmetries in the moisture origin of Antarctic precipitation, Geophys, Res. Lett., 36, L22803, doi:10.1029/2009GL040242, 2009.

Soderberg, K., Good, S. P., O'Connor, M., Wang, L., Ryan, K., and Caylor, K. K.: Using atmospheric trajectories to model the isotopic composition of rainfall in central Kenya, Ecosphere, 4(3): 1-18, 2013.

Tan, L. C., Cai, Y. J., Cheng, H., An, Z.S., and Edwards, R. L.: Summer monsoon precipitation variations in central China over the past 750 years derived from a high-resolution absoluted-dated stalagmite. Palaeogeogr. Palaeoclimatol. Palaeoecol., 280, 432-439, 2009.

Tian, L., Masson-Delmotte, V., Stievenard, M., Yao, T., and Jouzel, J.: Tibetan Plateau summer monsoon northward extent revealed by measurements of water stable isotopes, J. Geophys. Res., 106, D22, 28081-28088, 2001.

Tierney, J. E., Russell, J. M., Huang, Y. S., Sinninghe Damsté, J. S., Hopmans, E. C., and Cohen, A. S.: Northern hemisphere controls on tropical southeast Africa climate during the past 60000 years, Science, 322, 252-255, 2008.

Tremoy, G., Vimeux, F., Mayaki, S., Souley, I., Cattani, O., Risi, C., Favreau, G., and Oi, M.: A 1-year long $\delta^{18}O$ record of water vapor in Niamey (Niger) reveals insightful atmospheric processes at different timescales, Geophys. Res. Lett., 39, L08805, doi:10.1029/2012GL051298, 2012.

Vimeus, F., Tremoy, G., Risi, C., and Gallaire, R.: A strong control of the South American SeeSaw on the intra-seasonal variability of the isotopic composition of precipitation in the Bolinian Andes, Earth. Planet. Sci. Lett., 307, 47-58, 2011.

Vuille, M., Werner, M., Bradley, R. S., and Keimig, F.: Stable isotopes in precipitation in the Asian monsoon region, J. Geophys. Res., 110, D23108, doi:10.1029/2005JD006022, 2005.

Vuille, M., Werner, M., Bradley, R. S., and Keimig, F.: Stable isotopes in precipitation in the Asian monsoon region, J. Geophys. Res., 110, D23108, doi: 10.1029/2005JD006022, 2005.

Wang, B. and Lin, H.: Rainy season of the Asian-Pacific summer monsoon, J. Climate, 15, 386-398, 2002.

Wang, B. and Xu, X. H.: Northern Hemisphere summer monsoon singularities and climatological intraseasonal oscillation, J. Climate, 10, 1171-1185, 1997.

Wang, Y. J., Cheng, H., Edwards, R. L., An, Z. S., Wu, J. Y., Chen, C. C., and Dorale, J. A.: A high-resolution absolute-dated Late Pleistocene Monsoon record from Hulu Cave, China, Science, 294, 2345-2348, 2001.

Wang, Y. J., Cheng, H., Edwards, R. L., Kong, X. G., Shao, X. H., Chen, S. T., Wu, J. Y., Jiang, X. Y., Wang, X. F., and An, Z. S.: Millennial-and orbital-scale changes in the East Asian Monsoon over the past 224,000 years, Nature, 451, 1090-1093, 2008.

Werner, M., Langebroek, P. M., Carlsen, T., Herold, M., and Lohmann, G.: Stable water isotopes in the ECHAM5 general circulation model: Toward high-resolution isotope modeling on a global scale, J. Geophy. Res., 116, D15109, doi:10.1029/2011JD015681.

Xie, L. H., Wei, G. J., Deng, W. F., and Zhao, X. L.: Daily $\delta^{18}O$ and δD of precipitations from 2007 to 2009 in Guangzhou, South China: Implications for changes of moisture sources, J. Hydrol, 400, 477-489, 2011.

Yang, X. X., Yao, T. D., Yang, W. L., Xu, B. Q., He, Y., and Qu, D. M.: Isotopic signal of earlier summer monsoon onset in the Bay of Bengal, J. Climate, 25, 2509-2515, doi:10.1175/JCLI-D-11-00180.1, 2012.

Yuan, D. X., Cheng, H., Edwards, R. L., Dykoski, C. A., Kelly, M. J., Zhang, M. L., Qing, J. M., Lin, Y. S., Wang, Y. J., Wu, J. Y., Dorale, J. A., An, Z. S., and Cai, Y. J.: Timing, duration and transition of the last interglacial Asian monsoon, Science, 304, 575-578, 2004.

Zhang, P. Z., Cheng, H., Edwards, R. L., Chen, F. H., Wang, Y. J., Yang, X. L., Liu, J., Tan, M., Wang, X. F., Liu, J. H., An, C, L., Dai, Z. B., Zhou, J., Zhang, D. Z., Jia, J. H., Jin, L. Y., and

Johnson, K. R.: A test of climate, sun, and culture relationships from an 1810-year Chinese cave record, Science, 322, 940-942, 2008.