Linkage between precipitation isotopes and water vapor sources in the monsoon margin: Evidence from arid areas of Northwest China (Postprint)

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Abstract

The isotope composition in precipitation has been widely considered as a tracer of monsoon activity. Compared with the coastal region, the monsoon margin usually has limited precipitation with large fluctuation and is usually sensitive to climate change. The water resource management in the monsoon margin should be better planned by understanding the composition of precipitation isotope and its influencing factors. In this study, the precipitation samples were collected at five sampling sites (Baiyin City, Kongtong District, Maqu County, Wudu District, and Yinchuan City) of the monsoon margin in the northwest of China in 2022 to analyze the characteristics of stable hydrogen (δD) and oxygen ($ $18O) isotopes. We analyzed the impact of meteorological factors (temperature, precipitation, and relative humidity) on the composition of precipitation isotope at daily level by regression analysis, utilized the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT)-based backward trajectory model to simulate the air mass trajectory of precipitation events, and adopted the potential source contribution function (PSCF) and concentration weighted trajectory (CWT) to analyze the water vapor sources. The results showed that compared with the global meteoric water line (GMWL), the slope of the local meteoric water line (LMWL; δD=7.34$ $18O-1.16) was lower, indicating the existence of strong regional evaporation in the study area. Temperature significantly contributed to $ $18O value, while relative humidity had a significant negative effect on $ $18O value. Through the backward trajectory analysis, we found eight primary locations that were responsible for the water vapor sources of precipitation in the study area, of which moisture from the Indian Ocean to South China Sea (ITSC) and the western continental (CW) had the greatest influence on precipitation in the study area. The hydrogen and oxygen isotopes in precipitation are significantly influenced by the sources and transportation paths of air mass. In addition, the results of PSCF and CWT analysis showed that the water vapor source areas were primarily distributed in the south and northwest direction of the study area.

Full Text

Preamble

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Linkage between precipitation isotopes and water vapor sources in the monsoon margin: Evidence from arid areas of Northwest China

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Abstract

The isotopic composition of precipitation is widely recognized as a tracer of monsoon activity. Compared with coastal regions, monsoon margins typically experience limited precipitation with high variability and are particularly sensitive to climate change. Effective water resource management in these marginal zones requires a thorough understanding of precipitation isotope composition and its controlling factors. This study collected precipitation samples from five sites (Baiyin City, Kongtong District, Maqu County, Wudu District, and Yinchuan City) located along the monsoon margin in northwestern China throughout 2022 to analyze stable hydrogen (δD) and oxygen (δ^{18}O) isotope characteristics. Regression analysis was employed to examine the influence of meteorological factors (temperature, precipitation, and relative humidity) on precipitation isotope composition at the daily scale. The Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model was used to simulate air mass trajectories during precipitation events, while the Potential Source Contribution Function (PSCF) and Concentration Weighted Trajectory (CWT) methods were applied to analyze water vapor sources. The results revealed that the Local Meteoric Water Line (LMWL; $\delta D = 7.34\delta^{18}O - 1.16$) had a lower slope than the Global Meteoric Water Line (GMWL), indicating strong regional evaporation in the study area. Temperature exhibited a significant positive effect on δ^{18}O values, whereas relative humidity showed a significant negative effect. Backward trajectory analysis identified eight primary source regions for precipitation water vapor, with moisture from the Indian Ocean to South China Sea (ITSC) and western continental (CW) sources having the greatest influence. Hydrogen and oxygen isotopes in precipitation were significantly affected by both the source and transport pathways of air masses. Furthermore, PSCF and CWT analyses showed that water vapor source areas were predominantly distributed to the south and northwest of the study area.

Keywords: water vapor; monsoon margin; stable water isotope; transport trajectory; air mass; d-excess; δ^{18}O; δD

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1 Introduction

As the primary input to terrestrial water resources, precipitation constitutes a critical component of the hydrological cycle and plays a vital role in economic development and ecological stability, particularly in inland and arid regions. Although heavy isotopes of hydrogen (δ^2H, also expressed as δD) and oxygen (δ^{18}O) occur in trace amounts in precipitation, they are highly sensitive to environmental changes and can record information about atmospheric processes such as water transport, condensation, and exchange as air masses move from their source regions to precipitation sites [**?**, **?**]. As natural tracers in precipitation, stable δ^2H and δ^{18}O isotopes are widely used to investigate moisture sources [**?**, **?**, **?**, **?**, **?**, **?**].

Gimeno et al. (2012) summarized available methods for identifying moisture sources, including the analytical box method, physical tracer (isotope) method, and numerical tracer method. The physical water vapor tracer method, which incorporates both vertical and horizontal atmospheric processes, enables integration with global climate models and Lagrangian frameworks. In recent years, this approach has been extensively applied to analyze water vapor sources by tracking air mass movements [**?**, **?**, **?**].

Stable δ^2H and δ^{18}O isotopes in precipitation are intrinsic components of water molecules, and their compositional variations depend on moisture source, meteorological conditions, and transport mechanisms [**?**]. The processes controlling isotopic fractionation in precipitation have attracted considerable research attention [?, ?, ?, ?]. Due to abundant precipitation, numerous studies have examined how water vapor sources influence precipitation isotopes in monsoon regions, investigating the effects of various moisture sources on isotopic variations across different scales based on convective activity, cloud formation, and air trajectories [?, ?]. For example, decreasing δ^{18}O values in Tibetan Plateau precipitation during the early monsoon season (late May to early June) can be attributed to changes in water sources [?]. Additionally, convective processes may alter water vapor isotopic composition in source regions, while vapor transport itself affects isotopic composition in precipitation [?, ?, ?, ?, ?]. Spatially, temperature, amount, and altitude effects represent important factors influencing isotopic composition [?, ?, ?, ?]. However, many studies have also found associations between precipitation isotope composition and the location and/or intensity of upstream convective activities [?]. Furthermore, falling raindrops undergo isotopic fractionation when passing through unsaturated air, known as sub-cloud secondary evaporation, which modifies isotopic composition [?].

Deuterium excess (d-excess, calculated as δD -8δ^{18}O) reflects the evaporation rate in precipitation source areas, with high d-excess values typically indicating low relative humidity and intense evaporation [?]. Compared with monsoon-dominated coastal regions, monsoon margins typically receive limited precipitation with large fluctuations and are highly sensitive to climate change. Li et al. (1988) first proposed the concept of the "monsoon triangle," identifying a climatically sensitive region in China during the Quaternary period where circulation patterns, vegetation, soils, and climate underwent substantial changes between glacial and interglacial periods. The western vertex of this "monsoon triangle" extends deep into the continent, while the other two vertices are near the sea, with the western vertex corresponding to the monsoon margin. After long-range transport, air masses reaching the monsoon margin typically have complex origins, and frequent precipitation extremes can occur in such arid climates. Research in monsoon margins is therefore an important scientific topic, with modern precipitation isotope studies providing essential foundations for paleoclimate proxies. A systematic and synchronous observation network of precipitation isotopes in monsoon margins not only enhances understanding of evaporation and condensation processes under arid conditions but also holds great significance for ecological protection and sustainable development in water-scarce regions.

The objectives of this study are to: (1) examine the linkage between water vapor sources and precipitation stable isotopes (δ^{18}O and δD) in monsoon margins under arid conditions using Lagrangian methods; and (2) quantify the influence of different water vapor sources on isotopic characteristics.

2.1 Study Area

Five meteorological stations were selected as sampling sites in the East Asian monsoon margin area (also known as the "monsoon triangle" margin), including Baiyin City, Kongtong District, Maqu County, and Wudu District in Gansu Province, plus Yinchuan City in Ningxia Hui Autonomous Region, China [Figure 1: see original paper]. Elevations range from 1010 m a.s.l. in Yinchuan City to 3471 m a.s.l. in Maqu County (Table 1). The region has a dry continental monsoon climate with unevenly distributed annual precipitation and intense evaporation [**?**]. The average annual temperature is 9.29°C, and average annual precipitation is 394.66 mm, with more rainfall in summer and autumn and less rain and snow in spring and winter. This network corresponds to the western vertex of China' s "monsoon triangle" [**?**].

2.2 Isotope Data

Precipitation was collected using funneled polyethylene bottles with 1 L capacity placed at each sampling site. To prevent evaporation, samples were collected after each precipitation event, defined as collection of more than 1 mL of water. After collection, water samples were transferred to sealed 50 mL polyethylene bottles and stored in a cool place. Solid precipitation was placed in zip-locked bags at room temperature after collection, then transferred to polyethylene bottles after melting. Basic meteorological information (temperature, humidity, wind direction, wind speed, etc.) was recorded during each precipitation event. A total of 236 precipitation samples were collected across the five sites throughout 2022.

Water samples were analyzed at the Stable Isotope Laboratory, College of Geography and Environmental Science, Northwest Normal University, China. A DLT-100 liquid water isotope analyzer (Los Gatos Research, San Jose, USA) measured values of ^{1}H, ^{2}H, ^{3}H, ^{16}O, δ^{17}O, and ^{18}O. The analytical precision was within \$±\$0.6‰ for δD and \$±\$0.2‰ for δ^{18}O. Isotopic values were expressed as per mil (‰) deviations relative to Vienna Standard Mean Ocean Water (VSMOW) [**?**]:

$$\delta = \frac{R_{\text{sample}} - R_{\text{standard}}}{R_{\text{standard}}} \times 1000 \quad (1)$$

where δ represents the per mil difference relative to VSMOW, R_{sample} is the ratio of heavy to light isotopes in the water sample (D/H and ^{18}O/^{16}O for δD and δ^{18}O, respectively), and R_{standard} is the corresponding isotopic ratio in VSMOW.

Surface meteorological data (temperature, wind direction, wind speed, and precipitation) were obtained from the China Meteorological Data Network (http://data.cma.cn/dat). Upper-air meteorological data from the National Centers for Environmental Prediction (http://ready.arl.noaa.gov/archives.php) were used for air mass backward trajectory and potential source area analyses.

2.3 Methodology

This study employed the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model to simulate air mass trajectories during precipitation events. The Potential Source Contribution Function (PSCF) and Concentration Weighted Trajectory (CWT) methods were used to analyze precipitation water vapor sources.

2.3.1 HYSPLIT Model

The HYSPLIT model, developed by the National Oceanic and Atmospheric Administration (NOAA) and the Australian Bureau of Meteorology, simulates airflow movement, deposition, and dispersion patterns and is widely used to track precipitation air mass sources and pathways. The model employs a Lagrangian method for advection and diffusion and an Eulerian method for concentration calculations [**?**]. MeteoInfo backward trajectory clustering analysis based on HYSPLIT was used for water vapor source analysis [**?**]. Global Data Assimilation System (GDAS) data were imported into MeteoInfo software (Chinese Academy of Meteorological Sciences, Beijing, China) to conduct backward trajectory simulations for precipitation events in the study area, followed by trajectory clustering.

2.3.2 PSCF Analysis

PSCF analysis identifies potential source locations based on backward trajectory clustering results. Considering the environmental significance of d-excess [**?**, **?**, **?**, **?**, **?**], this study used the average d-excess value as a threshold to analyze precipitation potential source areas. Trajectories with d-excess values exceeding the average were counted as potential trajectories, while others were not [**?**, **?**]. The PSCF value represents the ratio of trajectories passing through a target grid (m) to the total number of trajectories (n), calculated as:

$$\mathrm{PSCF} = \frac{m}{n} \quad (2)$$

When the number of trajectories passing through a target grid (m) is too small, the probability function results may deviate from actual conditions. To ensure PSCF accuracy, a weighting factor w was introduced following Zeng and Hopke (1989):

$$w_{\text{PSCF}} = \begin{cases} 1.00 & \text{if } n > 80 \\ 0.70 & \text{if } 20 < n \leq 80 \\ 0.42 & \text{if } 10 < n \leq 20 \\ 0.05 & \text{if } n \leq 10 \end{cases} \quad (3)$$

where w_{PSCF} is the PSCF weight.

2.3.3 CWT Analysis

In addition to PSCF analysis, CWT analysis was employed to identify potential source locations of trajectories [?]. This method considers the spatial distribution of trajectories and corresponding isotopic characteristics [?, ?]. The CWT calculation formula is:

$$C_{ij} = \frac{\sum_{k=1}^{n} C_k \tau_{ijk}}{\sum_{k=1}^{n} \tau_{ijk}} \quad (4)$$

where C_{ij} is the weighted average d-excess value in grid (i, j) (‰/m^3), k is the trajectory index, n is the total number of trajectories, C_k is the d-excess value when trajectory k passes through grid (i, j), and τ_{ijk} is the residence time of trajectory k in grid (i, j). High CWT values indicate greater potential contribution from specific locations. To ensure CWT accuracy when trajectory endpoints passing through a grid are too few, the same weighting factor w as in PSCF was applied [?].

3.1.1 Spatial and Temporal Variations of Hydrogen and Oxygen Isotopes

The summer monsoon transports water vapor from tropical and subtropical oceans to inland areas [?]. Monsoon moisture typically begins in mid-May, advances northward gradually, and retreats completely by mid-October [?]. During June–September 2022, monthly precipitation ranged from 2.60 mm (September in Baiyin City) to 246.90 mm (August in Kongtong District). July and August were periods of relatively frequent precipitation events, with monsoon circulation delivering substantial moisture to the monsoon margin. Temperatures fluctuated between 3.50°C and 29.50°C during June–September 2022, averaging 18.20°C. Among sampling sites, Maqu County exhibited relatively low temperatures (3.50°C–17.10°C, mean 11.70°C), primarily due to its high altitude and plateau climate characterized by long, cold winters and short, cool summers. δD values during June–September 2022 ranged from -145.35‰ to 47.18‰ (mean -37.79‰), while δ^{18}O values ranged from -19.34‰ to 7.42‰ (mean -5.31‰) (Table 2). These results fall within the range of stable hydrogen and oxygen isotopes in precipitation for the arid region of Northwest China (δD: -263.20‰ to 59.00‰; δ^{18}O: -33.40‰ to 8.50‰) [?].

3.1.2 Local Meteoric Water Line (LMWL)

Craig (1961) established a linear relationship between δD and δ^{18}O in natural water samples: δD = 8.00δ^{18}O + 10.00, known as the Global Meteoric Water Line (GMWL). Rozanski et al. (1993) updated this to δD = 8.17δ^{18}O + 10.56 using global precipitation isotope data. Based on 1815 months of observed precipitation isotope data from China, the Chinese Meteoric Water Line is δD = 7.80δ^{18}O + 8.70 [?], while high-resolution nationwide gridded isotope data (431,136 grids) yield δD = 7.40δ^{18}O + 5.50 [?], both generally similar to the global mean.

Due to climatic differences, precipitation isotopic composition varies spatially. Strong evaporation causes the water line equation to deviate from the GMWL slope of 8. Higher temperatures intensify sub-cloud evaporation, resulting in smaller slopes and intercepts [?]. The LMWL for the summer half-year (March-September) was δD = 6.85δ^{18}O -2.11, while for the winter half-year (October-February) it was δD = 6.66δ^{18}O -7.48 (Fig. 2a [Figure 2: see original paper]). Some discrete points in Figure 2 were distributed to the right of the meteoric water line, indicating strong sub-cloud secondary evaporation in the study area. The summer LMWL slope exceeded the winter slope, reflecting greater precipitation and higher relative humidity in summer. As shown in Figure 2b, Kongtong District had the steepest LMWL slope (8.16), followed by Baiyin City (8.12), Wudu District (7.43), Yinchuan City (6.79), and Maqu County (4.68). LMWL intercepts were highest in Kongtong District (10.52), followed by Yinchuan City (0.75), Wudu District (-1.27), Baiyin City (-2.46), and Maqu County (-27.75). The overall study area LMWL was δD = 7.34δ^{18}O -1.16 (Fig. 2c [Figure 2: see original paper]), lower than global [?] and national [?] values, primarily due to low humidity and strong evaporation in the arid region, which enriches stable δD and δ^{18}O isotopes in precipitation.

3.1.3 Environmental Effects

Meteorological factors including temperature, precipitation, and relative humidity are considered primary environmental controls on precipitation isotope composition. This study examined relationships between δ^{18}O values and meteorological factors at the daily scale. Results showed a significant positive correlation between δ^{18}O and temperature (δ^{18}O = 0.24Tem -9.59, $R^2 = 0.15$, $P < 0.001$; Tem = temperature). The temperature effect at individual sites was weaker than for the entire study area, with significant positive correlation observed only in Kongtong District ($R^2 = 0.13$, $P < 0.050$). Maqu County, located in a continental alpine region with consistently low temperatures and a long cold season, and Wudu District, with consistently high temperatures, abundant precipitation, and high relative humidity, showed no significant temperature effects. A significant negative correlation existed between δ^{18}O and relative humidity across the East Asian monsoon margin (δ^{18}O = -0.16RH + 5.09, $R^2 = 0.18$, $P < 0.001$; RH = relative humidity). A negative correlation was also observed between δ^{18}O and precipitation (δ^{18}O = -0.05Pre -5.82, $R^2 = 0.01$, $P = 0.104$; Pre = precipitation), though this relationship was not statistically significant at most sites at the 0.05 level.

3.2 Backward Trajectory Analysis

The HYSPLIT-based backward trajectory model effectively simulates airflow movement. Each trajectory was calculated for 10 days (240 h) before precipitation events, approximating the maximum residence time of water vapor in the atmosphere [?, ?]. Trajectories were computed at 6-hour intervals (00:00, 06:00, 12:00, and 18:00 Beijing Time) on precipitation days, with a starting height of 1500 m above ground level for each site. Baiyin City and Wudu District were primarily influenced by continental water vapor, with northwest continental moisture having the greatest impact on Baiyin City (49.93% of total water vapor) (Fig. 3 [Figure 3: see original paper]). Kongtong District air masses originated mainly from the northwestern (37.36%), southeastern (23.70%), and western (23.28%) continents, with 15.66% of water vapor from the Black Sea. Maqu County was predominantly affected by westerly flows: 31.50% from the western continent, 28.68% from the Mediterranean Sea, and 13.82% from the Atlantic Ocean, plus influences from the southeast continent and Indian Ocean. Wudu District received its largest influence from the western continent (48.63% of total water vapor). Yinchuan City was mainly affected by northwest continental water vapor (78.70%), including 24.32% from the direction of Russia, plus a minor local water vapor cycle (21.30%).

3.3.1 Identification of Moisture Sources

To further investigate water vapor sources in the monsoon margin, backward trajectories were simulated for 236 precipitation events from January to December 2022. Water samples were collected during each precipitation event, defined as collection of more than 1 mL of water. Following common practice in other studies, a 10-day trajectory duration before precipitation events was adopted. Based on HYSPLIT backward trajectory results, moisture sources were classified into eight types (Table 3 ; Fig. 4 [Figure 4: see original paper]): continental moisture from northwest (CNW), continental moisture from west (CW), continental moisture from proximity region (CP), continental moisture from southwest (CSW), continental moisture from southeast (CSE), moisture from the Indian Ocean to South China Sea (ITSC), moisture from the Atlantic Ocean (OA), and moisture from polar region (PR).

For CNW, the average air mass trajectory length was 7133 km. In 2022, 33 precipitation events (13.98% of the total 236 events) were associated with CNW, contributing approximately 12.00% of total precipitation and occurring mainly during the summer half-year (May–September). These air masses originated from the northwest continent (northern Siberia, Mongolian Plateau) and affected the study area with partial local recycled water vapor, characterized by low relative humidity and high δD and δ^{18}O values while delivering little precipitation.

For CW, the average trajectory length was 6011 km. In 2022, 76 precipitation events (32.20% of total events) were related to CW, contributing 21.40% of total precipitation in the monsoon margin. These air masses originated from Western Eurasia and reached the study area through horizontal transport, indicating predominant westerly influence, particularly in winter when CW contributed a high percentage of precipitation with relatively high d-excess values.

For CP, the average trajectory length was 3140 km. In 2022, 13 precipitation events (5.51% of total events) were associated with CP, contributing 2.90% of total precipitation. These air masses came from continental areas near the study site, with precipitation events concentrated around the monsoon period (May–October). This air mass type had high relative humidity but produced minimal precipitation and the lowest d-excess values.

For CSW, the average trajectory length was 3152 km. In 2022, 10 precipitation events (4.24% of total events) were related to CSW, contributing about 2.10% of total precipitation. These air masses originated from the southwest continent near the study area (India and Bay of Bengal), with precipitation concentrated in October after the summer monsoon, characterized by high relative humidity and the lowest δD and δ^{18}O values.

For CSE, the average trajectory length was 3611 km. In 2022, 9 precipitation events (3.81% of total events) were associated with CSE, contributing about 6.30% of total precipitation. These air masses came from the southeast continent and Yellow Sea, with precipitation derived mainly from the southeast monsoon during June–September each year. This air mass type had high relative humidity, high temperature, and strong evaporation, producing the highest d-excess values.

For ITSC, the average trajectory length was 5078 km. In 2022, 79 precipitation events (33.47% of total events) were related to ITSC, contributing about 50.00% of total precipitation. These air masses originated from the Indian Ocean, Arabian Sea, and South China Sea, with precipitation occurring mainly during June–September. At the monsoon onset, ITSC air masses carrying abundant moisture passed through southwestern China at high speed, delivering substantial precipitation to the study area and exhibiting low δD and δ^{18}O values.

For OA, the average trajectory length was 16,815 km. In 2022, 10 precipitation events (4.24% of total events) were associated with OA, contributing about 2.50% of total precipitation. These air masses originated from the Atlantic Ocean and Mediterranean Sea, reaching the study area through zonal transport, with precipitation occurring mainly during May–July. Although relatively dry, long-distance transport gradually depleted heavy isotopes in water vapor, resulting in lower d-excess values.

For PR, the average trajectory length was 13,121 km. In 2022, 6 precipitation events (2.54% of total events) were associated with PR, contributing about 2.90% of total precipitation. These air masses originated from the Arctic Ocean and were transported through the northwest continent. Despite their oceanic origin, long travel paths resulted in low relative humidity. After passing over Siberia and the Mongolian Plateau, this air mass type exhibited the lowest d-excess values.

3.3.2 Identification of Water Vapor Source Areas by PSCF and CWT

PSCF analysis determined the magnitude of impact from potential water vapor source areas by calculating the proportion of trajectories exceeding the d-excess threshold for each grid. CWT analysis then identified the weighted concentration magnitude of potential evaporation source areas. In Baiyin City, water vapor originated mainly from the west and southwest of the study area (Fig. 5 [Figure 5: see original paper]). Kongtong District received moisture primarily from surrounding areas and the southwest direction. Maqu County precipitation sources were distributed mainly to the southwest of the study area. Wudu District water vapor came predominantly from the south, while Yinchuan City sources were distributed in the south and southeast. CWT analysis results showed that Baiyin City and Wudu District were mainly affected by CW and ITSC, whereas Kongtong District, Maqu County, and Yinchuan City were influenced primarily by CP, ITSC, and CW.

3.3.3 Relationship Between d-excess Value and Wind

The d-excess value reflects the climatic environment of water vapor source areas [?]. Relatively dry moisture sources with low humidity and rapid evaporation produce high d-excess values, while moist sources yield low d-excess values [?]. Figure 6 [Figure 6: see original paper] illustrates the relationship between d-excess values (interpolated from all precipitation events) and wind characteristics (speed and direction) for all 2022 precipitation events at the five sampling sites. High d-excess values in Baiyin City appeared mainly in precipitation from air masses originating from southern and southwestern China, with a small portion from southeastern China at low wind speeds (<1.50 m/s). In Kongtong District, high d-excess values occurred primarily in precipitation from air masses from southeastern and southwestern China, with a small portion from northwestern China at high wind speeds (3.00-4.00 m/s). Maqu County, with abundant precipitation, showed high d-excess values mainly in air masses from southeastern and southwestern China, plus a small amount from northeastern China. In Wudu District, high d-excess values appeared in precipitation from air masses originating from southeastern, southern, and southwestern China at lower wind speeds (<1.50 m/s). Yinchuan City exhibited high d-excess values mainly in precipitation from air masses from southeastern and southwestern China.

4.1 LMWL in the Monsoon Margin

The composition of δ^2H and δ^{18}O isotopes in precipitation air masses varies considerably, and differences in isotopic composition can reflect water vapor sources and the degree of evaporation [?, ?, ?]. This study derived the atmospheric water line equation for the western fringe of the "monsoon triangle" using least squares regression. Compared with the GMWL, the LMWL slope in the study area was relatively low, indicating that the precipitation process was accompanied by secondary evaporation. Furthermore, based on differences in d-excess values between seasons, secondary evaporation was more intense during the winter half-year than the summer half-year, with winter d-excess values being lower due to reduced relative humidity.

4.2 Identification of Water Vapor Sources

Precipitation in a given area comprises both locally evaporated water vapor and long-distance transported moisture. Externally transported water vapor is essential for generating intense precipitation [?, ?, ?], particularly in northwest inland areas where air humidity is low and evaporation is intense. Understanding the specific influence of different water vapor sources is crucial for comprehending water cycle processes in arid regions. Zeng et al. (2020) identified westerly water vapor as the primary moisture source in northwest China, consistent with our backward trajectory clustering results. Quantitative trajectory analysis revealed that precipitation events related to CW and ITSC accounted for large proportions. Due to low relative humidity, CW-generated precipitation events were mostly drizzle or light rain, with water vapor having nearly completely evaporated during long-distance transport. ITSC contributed the highest proportion of precipitation, with events concentrated during the monsoon period (June-September). ITSC air masses, carrying abundant moisture, passed through southern and southwestern China at high speeds, delivering substantial precipitation to northwest inland areas. Claus et al. (2021), Wu et al. (2021), and

Wu and Bedaso (2022) concluded that backward trajectory tracking and isotopic second-order variables (i.e., d-excess) can reflect the degree of imbalance in evaporation-condensation processes in water vapor source areas, and that d-excess serves as an important indicator for tracing water vapor sources. Based on d-excess wind rose diagrams (Fig. 6 [Figure 6: see original paper]), precipitation in the monsoon margin was primarily influenced by monsoon moisture and westerly moisture. Although sampling sites were established in the monsoon margin, future studies should include more sites over longer durations and larger spatial coverage.

4.3 Influencing Factors of Precipitation Isotopes

Dansgaard (1964) identified correlations between precipitation isotopes and environmental factors. Air humidity and temperature are important meteorological conditions affecting precipitation isotopes [**?**, **?**, **?**]. This study examined correlations between precipitation isotopes and meteorological factors, finding that δ^{18}O values were positively correlated with temperature and negatively correlated with relative humidity in the study area. Compared with temperature and relative humidity, precipitation showed weaker correlation with isotopes due to low precipitation intensity. Water vapor sources are also considered important factors affecting precipitation isotope variation [**?**, **?**, **?**]. Precipitation formed predominantly from dry continental water vapor tended to have higher d-excess values, while precipitation from moist marine vapor had lower d-excess values in the monsoon margin. Additionally, air mass transport duration and distance are vital for modifying isotopic composition in precipitation.

In this study, relative humidity values for air masses from CW, CNW, OA, and CP were 62.37%, 63.58%, 70.79%, and 79.60%, respectively (Table 3). d-excess values for these four sources decreased gradually with increasing relative humidity. Precipitation from CSE had the highest d-excess value (84.90%), corresponding to its relatively high temperature and short transport path with less rainout. ITSC air masses had the highest temperature compared with continental air masses and produced considerable precipitation. Heavy isotopes in water vapor were continuously depleted along the transport path due to air mass movement. Relative humidity was relatively low in air masses from PR, CNW, and CW, and d-excess values decreased steadily with extended transport paths.

5 Conclusions

This study analyzed precipitation isotope data collected throughout 2022 in the monsoon margin and used the HYSPLIT-based backward trajectory model, PSCF analysis, and CWT analysis to investigate water vapor sources. Regression analysis defined the monsoon margin LMWL as $\delta D = 7.34\delta^{18}O$ -1.16. The lower slope and intercept compared with the GMWL ($\delta D = 8.17\delta^{18}O + 10.56$) indicated strong regional evaporation. Additionally, the atmospheric water line slope was higher in summer than winter due to greater humidity in summer.

Analysis of relationships between $\delta^{18}O$ values and meteorological factors at the daily scale revealed significant positive temperature effects and significant negative relative humidity effects on $\delta^{18}O$. The composition of $\delta^{2}H$ and $\delta^{18}O$ isotopes was also strongly influenced by air mass trajectories. Eight source areas accounted for the majority of water vapor: CNW (13.98%), CW (32.20%), CP (5.51%), CSW (4.24%), CSE (3.81%), ITSC (33.47%), OA (4.24%), and PR (2.54%). Precipitation in the study area was predominantly caused by ITSC water vapor due to its high moisture content. Long water vapor transport distances increased isotopic loss from precipitation.

Understanding atmospheric precipitation processes is crucial for water resource management in arid and semi-arid regions. This study's relatively short duration (one year) represents a limitation; future research should employ multi-year precipitation data to analyze linkages between precipitation isotope composition and water vapor sources in arid areas.

Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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All authors approved the manuscript.

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Note: Figure translations are in progress. See original paper for figures.