Isotopic Characteristics of Precipitation and Water Vapor Source Analysis in the Kashi River Basin (Postprint)

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Abstract

Using atmospheric precipitation isotope data from July 2017 to June 2018 in the mountainous area of the Kashi River basin, together with meteorological records of temperature and precipitation in the basin's mountainous region, we analyzed the variation characteristics of $ $18O, δD, and deuterium excess (d-excess) in precipitation, discussed the relationship between $ $18O and temperature and precipitation amount, and traced the moisture sources of atmospheric precipitation in the basin's mountainous area using the HYSPLI model. The results show that: (1) $ $18O in precipitation within the basin exhibits significant seasonal variation, with $ $18O isotopes enriched in summer and depleted in winter. (2) The relationship between $ $18O and δD differs significantly among different precipitation types; in summer, evaporation fractionation of δD is greater than that of $ $18O, and the slope and intercept of the rainfall meteoric water line are smaller; in winter, evaporation fractionation of δD is significantly weakened, and the slope and intercept of the snowfall meteoric water line are larger. (3) Isotopes in atmospheric precipitation within the basin show a significant temperature effect, but the precipitation amount effect is not significant. (4) Moisture in atmospheric precipitation within the basin mainly originates from the Atlantic Ocean; influenced by long-distance moisture transport and the addition of considerable secondary evaporated water vapor along the way, deuterium excess values (d-excess) are generally high; however, deuterium excess in February is relatively low, which is related to the influence of the Arctic air mass source region having low temperature, high air humidity, and short moisture transport paths. (5) Precipitation in this basin during summer mainly originates from the westerly circulation and locally recycled moisture, while in winter it is jointly influenced by the westerly circulation and Arctic air masses; precipitation formed from Atlantic Ocean moisture accounts for 68.6% of the total precipitation in the study area, locally recycled moisture accounts for 17.1%, and precipitation

formed from Arctic Ocean moisture accounts for 14.3% of the total precipitation in the study area.

Full Text

Isotopic Characteristics and Water Vapor Sources of Precipitation in the Kashi River Basin

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Abstract

Using precipitation isotope data from July 2017 to June 2018 in the mountainous area of the Kashi River Basin, together with meteorological data on temperature and precipitation, we analyzed the seasonal variation characteristics of δ^{18}O, δD, and d-excess in precipitation and examined their relationships with temperature and precipitation amount. We employed the HYSPLIT model to trace and analyze the water vapor sources of atmospheric precipitation in the basin' s mountainous region. The results reveal: (1) The hydrogen and oxygen isotopes in precipitation exhibit pronounced seasonal variation, with enrichment in summer and depletion in winter, reflecting the influence of strong evaporation fractionation at high summer temperatures and weak fractionation at low winter temperatures. (2) The slope and intercept of the local meteoric water line (LMWL) are higher than those of the global meteoric water line, indicating significant influence from locally recycled water vapor at high altitudes. The relationship between δ^{18}O and δD differs markedly between precipitation types: in summer rainfall, evaporation fractionation of δD exceeds that of δ^{18}O, resulting in smaller slope and intercept values, whereas in winter snowfall, evaporation fractionation is notably weakened, yielding larger slope and intercept values. (3) Precipitation isotopes display a significant temperature effect (δ^{18}O = 0.73T - 18.21, R^2 = 0.66) but no significant precipitation amount effect at the annual scale. At the seasonal scale, autumn shows a weak precipitation amount effect due to abundant rainfall and relatively low temperatures. (4) The d-excess values in the basin are generally high, ranging from -7.8‰ to 32.7‰ with a mean of 16.8‰, exceeding the global average of 10‰. Seasonally, d-excess is high in summer and autumn when precipitation originates from the Atlantic Ocean, but low in winter and spring when influenced by Arctic air masses. (5) Summer and autumn precipitation derives primarily from westerly circulation and local recycled vapor, with Atlantic moisture accounting for 68.6% of total annual precipitation and local recycled vapor contributing 17.1%. Winter precipitation is jointly influenced by westerly circulation and Arctic air masses, with Arctic

moisture contributing 14.3% of total annual precipitation.

Keywords: Kashi River Basin; precipitation; stable isotope; water vapor source

1. Introduction

Hydrogen and oxygen stable isotopes are important components of water bodies and remain stable in nature [?]. As the primary source of terrestrial water cycling, atmospheric precipitation plays a crucial role in indicating climate change [?]. The hydrogen and oxygen stable isotopes in precipitation serve as natural tracers in the water cycle. Their variation is mainly related to climatic conditions in the water vapor source region and water vapor recycling during transport, while also being influenced by meteorological conditions at precipitation sites (such as temperature and precipitation amount) [?, ?]. Therefore, analyzing the composition of hydrogen and oxygen stable isotopes in precipitation can improve our understanding of water cycling processes [?].

International research on isotopes began relatively early. The International Atomic Energy Agency (IAEA) and the World Meteorological Organization (WMO) jointly operate the Global Network for Isotopes in Precipitation (GNIP) [?]. Craig [?] discovered a linear relationship between hydrogen and oxygen stable isotopes in precipitation, expressed as $\delta D = 8\delta^{18}O + 10‰$. Dansgaard [?] analyzed the spatiotemporal distribution characteristics of stable isotopes in precipitation and introduced fundamental concepts such as isotope effects and deuterium excess. In China, Zheng Shuhui et al. [?] first proposed the Chinese meteoric water line equation: $\delta D = 7.9\delta^{18}O + 8.2‰$. Zhang Xinping et al. [?] mapped the distribution of $\delta^{18}O$ across China and identified three major water vapor routes. Domestic scholars have extensively investigated water cycling processes in the Tibetan Plateau [?], North China [?], and southern China [?] using stable isotope techniques.

Currently, stable isotope technology has been widely applied in hydrological and water resource research in northwest China. Liu Xiaokang et al. [?] studied the interannual variation of hydrogen and oxygen isotopes and water vapor sources in the Tianshan Mountains using data from Urumqi and Hotan stations, exploring the influence of the westerlies on precipitation isotopes in Xinjiang. Feng Fang et al. [?] analyzed the impact of sub-cloud evaporation on summer precipitation isotopes in Xinjiang. Kong Yanglong et al. [?] examined the variation patterns of hydrogen and oxygen isotopes and d-excess at sites in the Urumqi River Basin, discussing the proportion of water vapor recycling in the Urumqi River. Jiang Xinhua et al. [?] analyzed the characteristics of atmospheric precipitation isotopes in the Ili River Valley and calculated the proportion of sub-cloud evaporation during summer in the region. However, GNIP stations in Xinjiang are limited to Urumqi and Hotan, providing limited coverage. The Kashi River Basin mountainous area is far from these two stations, and comprehensive research on annual stable isotopes and water vapor sources is lacking. As a typical mountainous river in Xinjiang, analyzing the relationship between hydrogen and oxygen isotope characteristics and water vapor sources in its precipitation is theoretically significant for understanding water vapor cycling processes, regional precipitation patterns, and precipitation formation mechanisms in the western Tianshan Mountains, and practically important for understanding atmospheric water vapor formation mechanisms and predicting future climate change.

2. Materials and Methods

2.1 Study Area The Kashi River, the second largest tributary of the upper Ili River, originates from the alpine glacier zone at the junction of the Tianshan Mountains and the Yilianhabierga Mountains. It flows westward to Yamadu near Dunmazha in Yining County, where it joins the Kunes River. The Kashi River Basin (43°25 -44°39 N, 81°50 -84°45 E) is located in the hinterland of the Eurasian continent and features a temperate continental climate. The basin covers a total area of 9,541 km^2 with a main stream length of 304 km [**?**]. The river source has an elevation of approximately 3,600 m, while the basin elevation ranges from 800 to 4,600 m, with higher terrain in the east and lower in the west. The river channel is straight with a feather-shaped pattern, featuring short and widely distributed tributaries such as the Zhaikou River and Baoerbaosi River [**?**].

[Figure 1: see original paper] Distribution of precipitation sampling point and hydrometeorological observation stations in mountainous areas of Kashi River Basin

2.2 Sample Collection and Analysis From July 2017 to June 2018, we collected 60 precipitation samples in the mountainous area of the Kashi River Basin in Nileke County, including 44 rainfall samples and 16 snowfall samples. The sampling site is located at 43°45 N, 82°16 E with an elevation of 1,502 m. At the onset of each precipitation event, rainfall was collected in a polyethylene plastic bucket placed in an open outdoor area. The start and end times of precipitation were recorded, and samples were immediately transferred to plastic bottles after the event. Bottle caps were sealed with wax and tape indoors to prevent evaporation, and samples were stored in a refrigerator at low temperature (<4°C). Snowfall collection followed a similar procedure: snow was collected and sealed, then allowed to melt naturally indoors before processing. All sampling equipment was kept dry before use to prevent contamination.

Meteorological data including relative humidity and precipitation were obtained from the Nileke Meteorological Station of the Xinjiang Uygur Autonomous Region Meteorological Information Center, located north of Nileke County, 60 km west of the sampling site. The hydrogen and oxygen stable isotopes in precipitation were analyzed using a DLT-100 liquid water stable isotope analyzer (Los Gatos Research Inc., USA) with precisions of \$±\$0.5‰ for δ^{18}O and \$±\$0.3‰ for δD. Results are expressed in per mil (‰) relative to Vienna Standard Mean Ocean Water (VSMOW):

$$\delta^{18}O = \left(\frac{R_{sample}}{R_{VSMOW}} - 1\right) \times 1000‰$$

where R_{sample} and R_{VSMOW} represent the isotope ratios of the precipitation sample and VSMOW, respectively.

The weighted average values of hydrogen and oxygen stable isotopes in precipitation were calculated as:

$$\delta_{weighted} = \frac{\sum_{i=1}^{n} P_i \delta_i}{\sum_{i=1}^{n} P_i}$$

where P_i is the precipitation amount for a single event, δ_i is the corresponding stable isotope value, and $\delta_{weighted}$ is the monthly weighted average.

2.3 HYSPLIT Model The HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) model is a professional meteorological model for calculating and analyzing atmospheric pollutant transport and diffusion trajectories [**?**]. This study used global daily reanalysis data (2.5°$×$2.5° resolution, 17 vertical levels) from the National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) to simulate water vapor source trajectories via the HYSPLIT backward trajectory method. The trajectory endpoint was set at the Nileke County site (43°45 N, 82°16 E) with an initial height of 2,000 m above ground level. To ensure comprehensive analysis, we also calculated trajectories at 3,000 m and 4,000 m heights. The simulation period covered 120 hours for each precipitation event to reveal water vapor source variations throughout the observation period. Based on the HYSPLIT-simulated trajectories, we estimated the contribution ratios of different water vapor sources to precipitation in the study area. Precipitation events were categorized by water vapor source (Atlantic Ocean, Arctic Ocean, and local vapor), and the proportion of precipitation formed by each source was calculated.

3. Results

3.1 Seasonal Variation of Precipitation Isotopes in the Kashi River Basin The δ^{18}O values in precipitation show substantial seasonal variation, ranging from -25.91‰ to 0.35‰ with a weighted mean of -9.91‰. Isotopic enrichment occurs in summer while depletion occurs in winter. From a monthly perspective (Table 1), maximum δ^{18}O values appear in July and minimum values in January; δD follows a similar pattern with maximum values in July and minimum values in January. This seasonal pattern reflects the dominant role of westerly moisture in this region, where heavy isotopes are enriched in summer and depleted in winter [**?**]. At the event scale, the highest δ^{18}O value (0.35‰, the only positive value) occurred on July 23, 2017, with a precipitation amount of 2.8 mm and daily mean temperature of 16.8°C. The high temperature and low precipitation caused significant sub-cloud evaporation, enriching the precipitation with heavy isotopes.

Previous studies based on GNIP data from the Urumqi River Basin revealed similar hydrogen and oxygen isotope variation patterns—enrichment in summer and depletion in winter—consistent with the Kashi River Basin and reflecting the annual cycle of typical continental climate in northwest China [?]. Comparison with precipitation δ^{18}O in monsoon-affected coastal regions of southeast China shows opposite seasonal characteristics, likely due to differences in latitude, location relative to oceans, and seasonal atmospheric circulation control, particularly the degree of monsoon influence [?]. Generally, in mid-high latitude continental regions, especially high-latitude inland areas, large temperature differences between winter and summer cause δ^{18}O to exhibit higher values in summer and lower values in winter due to the influence of continental air masses and significant local evaporation. In contrast, mid-low latitude coastal regions are clearly affected by monsoon climate: summer moisture from low-latitude oceans (Pacific and Indian Oceans) has high humidity and relatively low δ^{18}O, while winter air carried by westerlies has continental characteristics with low humidity, strong evaporation, and relatively high δ^{18}O [?].

[Figure 2: see original paper] Temporal variation trend of δ^{18}O in precipitation in the study area

3.2 Characteristics of the Local Meteoric Water Line The relationship between δ^{18}O and δD in atmospheric precipitation of the Kashi River Basin shows a significant linear correlation (Figure 3), yielding the local meteoric water line (LMWL) equation:

$$\delta D = 8.2\delta^{18}O + 16.8‰ \quad (R^2 = 0.98)$$

Both the slope and intercept of the Kashi River Basin LMWL are higher than those of the global meteoric water line (GMWL: δD = 8δ^{18}O + 10‰) and the LMWL of the lower Ili River (δD = 7.9δ^{18}O + 10.3‰), indicating strong influence from locally recycled water vapor in the study area. Comparing LMWLs for different precipitation types (Figure 4) reveals two key features: (1) The snowfall LMWL has higher slope and intercept values than the rainfall LMWL because snowfall occurs mainly in winter when low temperatures weaken sub-cloud evaporation. Rainfall occurs primarily in summer when higher temperatures enhance sub-cloud evaporation, resulting in lower slope and intercept values that are slightly below the GMWL, indicating strong sub-cloud secondary evaporation. (2) Both snowfall and rainfall LMWLs have high intercepts, demonstrating significant influence from locally recycled water vapor.

[Figure 3: see original paper] Local meteoric water line map of study area

[Figure 4: see original paper] Local meteoric water lines of different precipitation types in the study area

3.3 Isotope Effects

3.3.1 Temperature Effect Linear regression between monthly mean temperature and δ^{18}O yields:

$$\delta^{18}O = 0.73T - 18.21 \quad (R^2 = 0.66)$$

Precipitation δ^{18}O shows significant positive correlation with monthly mean temperature, indicating a strong temperature effect. As temperature increases, δ^{18}O becomes progressively enriched. Located in the inland region of northwest China at mid-high latitude, the Kashi River Basin experiences strong sub-cloud evaporation in summer, causing significant fractionation of light isotopes and δ^{18}O enrichment. In winter, low temperatures weaken sub-cloud evaporation, and secondary evaporated vapor undergoes adiabatic expansion during ascent, resulting in δ^{18}O depletion.

Similar temperature effects have been observed at Yining and Nileke stations in the Ili River Valley, with correlation coefficients of 0.71 and 0.73, respectively, both higher than at our sampling site, suggesting that the temperature effect weakens with increasing altitude in the Ili River Valley region. The relationship between d-excess and temperature can be divided into three parts (Figure 6): (1) At temperatures below 5°C (winter-spring), sub-cloud evaporation and water vapor recycling are weak, and isotopes are mainly controlled by fractionation, showing strong temperature effect. (2) At 5–15°C, increasing temperature enhances sub-cloud evaporation, but the δ^{18}O enrichment from evaporation is offset by depletion from recycled vapor, making temperature effect less obvious. (3) At 15–25°C (summer-autumn), high temperatures cause strong sub-cloud evaporation and isotopic fractionation, leading to δ^{18}O enrichment and significant temperature effect. During this period, d-excess becomes depleted with rising temperature, indicating that sub-cloud evaporation exceeds the depletion effect of water vapor recycling [**?**].

[Figure 5: see original paper] Relationship between precipitation δ^{18}O and temperature in the study area

[Figure 6: see original paper] Relationship between precipitation δ^{18}O, d-excess and temperature in the study area

3.3.2 Precipitation Amount Effect The relationship between δ^{18}O and precipitation amount (P) is expressed by linear regression as:

$$\delta^{18}O = 0.19P - 16.42 \quad (R^2 = 0.01)$$

Precipitation isotopes in the Kashi River Basin show no significant correlation with precipitation amount (Figure 7). This may be related to local climate conditions: the basin lies in a temperate continental climate zone where precipitation concentrates in summer and autumn when temperatures are high and temperature effects are significant, masking any precipitation amount effect. Generally, precipitation δ^{18}O in mid-high latitude continental regions is controlled by temperature effects, while coastal islands and tropical regions show precipitation amount effects [?]. In China, temperature effects dominate north of 35°N, whereas coastal and monsoon-affected regions show significant negative correlations between stable isotope ratios and precipitation amount [?].

[Figure 7: see original paper] Relationship between δ^{18}O and precipitation in atmospheric precipitation in the study area

At the seasonal scale (Table 2), autumn shows the most significant precipitation amount effect, followed by winter, while spring and summer show no effect. Autumn has abundant precipitation (second only to summer) but relatively low temperatures, so temperature effect does not completely mask the precipitation amount effect. Although summer has the highest precipitation, high temperatures strengthen the temperature effect, eliminating any precipitation amount effect. Similar patterns have been observed in the Heihe River Basin [?], Urumqi River [?], and Tuolai River [?], indicating that while annual precipitation amount effects are not significant in arid northwest China, seasonal effects cannot be ignored.

The relationship between δ^{18}O and precipitation in different seasons in the study area

3.4 Variation Characteristics of Deuterium Excess As shown in Figure 8, d-excess values in the mountainous area of the Kashi River Basin range from -7.8‰ to 32.7‰ with a mean of 16.8‰. Among 60 samples, 45 (75%) exceed the global average of 10‰. Variation in d-excess is primarily influenced by water vapor source region and transport pathways, as well as local meteorological factors [?]. Aizen et al.'s [?] study of Belukha glacier ice core records showed that precipitation from different vapor sources has distinct d-excess values: moisture from the Arctic Ocean yields low d-excess (<7.8‰), while Atlantic moisture yields d-excess ranging from 7.8‰ to 23.5‰, and terrestrial moisture yields even higher values.

Located on the windward slope of the western Tianshan Mountains and perennially influenced by westerlies, the study area experiences long-distance moisture transport. The basin' s high altitude and abundant vegetation enhance local water vapor recycling through plant transpiration, resulting in high annual d-excess values. At the monthly scale (Table 1), d-excess values vary significantly by month and remain high overall, except in January when the weighted average is only 6.8‰–significantly lower than other months. The two precipitation events on January 15 and 30, with d-excess values of 2.6‰ and 4.1‰, respectively, indicate that January moisture mainly originates from the Arctic Ocean.

[Figure 8: see original paper] Temporal variation of deuterium surplus in the study area

3.5 Influence of Water Vapor Sources on Precipitation Isotopes and d-excess The variation in d-excess is not only affected by local meteorological factors but also closely related to precipitation moisture sources and transport processes. Using the HYSPLIT backward trajectory model to cluster water vapor sources for 60 precipitation events (Figure 9), we selected typical events (monthly maximum precipitation events) for analysis. The results show that summer and autumn precipitation mainly originates from the Atlantic Ocean and Mediterranean Sea, transported by westerlies to the interior of the Eurasian continent. During transport, near-source oceanic moisture and local evaporated vapor continuously mix in, resulting in high d-excess weighted averages of 18.9‰ in summer and 17.1‰ in autumn. After October, Atlantic moisture decreases and temperature drops reduce local evaporated vapor along the transport path, causing d-excess to gradually decline to 14.5‰ in autumn—higher than winter but lower than summer.

Winter precipitation is jointly influenced by westerly circulation and polar air masses, with moisture sources shifting northward and transport distances shortening, reducing local evaporation along the path and yielding low d-excess values (10.6‰ in winter). In spring, moisture sources shift southward; Atlantic moisture yields d-excess values lower than in summer but higher than in winter. The highest d-excess value occurs in April when moisture originates from the Central Asian interior with low source humidity and significant local evaporation influence.

[Figure 9: see original paper] Track of monthly precipitation water vapor source in the output study area of hysplit model

We estimated the contribution ratios of different water vapor sources to precipitation in the study area based on HYSPLIT-simulated trajectories. Moisture from Xinjiang and Central Asia was classified as local evaporated vapor, moisture from Siberia and the Arctic region as Arctic Ocean vapor, and long-distance moisture from west of the Caspian Sea as Atlantic vapor. Table 3 shows that total annual precipitation in the study area was 256.8 mm, of which 212.3 mm (82.6%) formed from Atlantic vapor, 44.5 mm (17.1%) from local recycled vapor, and 36.8 mm (14.3%) from Arctic vapor. The seasonal distribution reveals that Atlantic vapor dominates summer and autumn precipitation, Arctic vapor mainly contributes in winter and spring, and local recycled vapor accounts for 17.4% of annual precipitation. The low d-excess value in January reflects strong Arctic air mass influence.

Rainfall from different water vapor sources and its percentage to total precipitation

The backward trajectory method has certain limitations in precisely estimating the contribution of local evaporation to precipitation, as oceanic moisture may mix with locally evaporated vapor during transport, which becomes part of the oceanic trajectory in the simulation, potentially overestimating the oceanic moisture contribution [?].

4. Conclusions

(1) The hydrogen and oxygen isotopes in precipitation of the Kashi River Basin mountainous area fluctuate widely (δ^{18}O: -25.91‰ to 0.35‰), with pronounced seasonal variation—enriched in summer and depleted in winter. This pattern aligns with the hydrogen and oxygen isotope variation characteristics of the Urumqi River Basin in the eastern Tianshan Mountains, reflecting the annual cycle of typical continental climate in northwest China.

(2) The local meteoric water line equation for the study area is δD = 8.2δ^{18}O + 16.8‰ (R^2 = 0.98), with slope and intercept values exceeding those of the global meteoric water line. The high slope and intercept reflect the significant influence of locally recycled water vapor in high-altitude areas of arid northwest China. The relationship between δ^{18}O and δD differs between precipitation types: summer rainfall shows stronger evaporation fractionation of δD than δ^{18}O with smaller slope and intercept values, while winter snowfall exhibits weakened evaporation fractionation with larger slope and intercept values.

(3) Precipitation isotopes in the study area show a significant temperature effect (δ^{18}O = 0.73T - 18.21, R^2 = 0.66) but no significant precipitation amount effect at the annual scale. At the seasonal scale, autumn precipitation is relatively abundant with lower temperatures, allowing a weak precipitation amount effect to emerge.

(4) The d-excess values in the basin are generally positive, ranging from -7.8‰ to 32.7‰ with a mean of 16.8‰, exceeding the global average of 10‰. At the annual scale, the high d-excess indicates strong influence from Atlantic moisture and local recycled vapor. Seasonally, d-excess is high in summer and autumn when precipitation originates from the Atlantic Ocean, but low in winter and spring when influenced by Arctic air masses.

(5) HYSPLIT model simulations indicate that summer and autumn moisture mainly originates from the Atlantic Ocean and local evaporation. Atlantic moisture accounts for 68.6% of total annual precipitation, local recycled vapor contributes 17.1%, and Arctic moisture contributes 14.3%, with clear seasonal differences in moisture sources.

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