Moisture Transport Mechanisms for Precipitation of Different Intensity Levels in the Yinchuan Plain During the Warm Season (Postprint)

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Abstract

Global warming accelerates regional water cycles and alters water vapor transport pathways; understanding the stable isotope characteristics of rainfall at different intensities and water vapor sources provides a basis for water resource utilization and drought-flood disaster prevention and control. Based on rainfall samples collected in the Yinchuan Plain during the summer half-year (May-October) of 2018–2020, this study investigates the variation characteristics of hydrogen and oxygen stable isotopes in rainfall of different intensities and their secondary evaporation effects, and analyzes the water vapor sources and potential evaporation source regions of rainfall using methods such as backward trajectory models and water vapor flux. The results show that: stable isotopes in rainfall of different intensities in the Yinchuan Plain during the summer half-year become more depleted with increasing rainfall intensity; d-excess values of light rain are negative while those of moderate and heavy rain are positive; the slope and intercept of the meteoric water line exhibit a decreasing trend with increasing rainfall intensity. The intensity of secondary evaporation increases with rising temperature and decreases with increasing rainfall amount, relative humidity, and raindrop diameter. Westerly water vapor is the dominant moisture source for rainfall in the Yinchuan Plain during the summer half-year, while light rain, moderate rain, and heavy rain are also influenced by terrestrial evaporation water vapor, Atlantic water vapor, and Pacific water vapor, respectively. Potential evaporation source regions have a greater impact on light rain, mainly located in the areas surrounding the study region and its northern, southern, and southeastern parts; those for moderate rain are mainly distributed in the areas surrounding the study region and its northwestern and southeastern parts; and those for heavy rain are mainly distributed in the areas surrounding the study region and its southeastern part.

Water Vapor Transport Mechanisms for Varied Precipitation Grades During the Summer Half-Year in Yinchuan Plain

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Abstract

Global climate warming accelerates regional water cycles and alters water vapor transport pathways. Understanding the stable isotopic characteristics of different precipitation grades and their moisture sources provides a scientific basis for water resource utilization and drought-flood disaster prevention. Based on precipitation samples collected during the summer half-years (May–October) of 2018–2020 in Yinchuan Plain, this study investigated the variation characteristics of hydrogen and oxygen stable isotopes in different precipitation grades and their secondary evaporation effects. Backward trajectory modeling and water vapor flux methods were employed to analyze moisture sources and potential evaporation source regions. Results show that stable isotope values in Yinchuan Plain during the summer half-year became increasingly depleted with higher precipitation grades. Light rain exhibited negative d-excess values, while moderate and heavy rains showed positive values. The slope and intercept of the local meteoric water line decreased with increasing precipitation magnitude. Secondary evaporation intensity increased with rising temperature but weakened with greater precipitation amount, relative humidity, and raindrop diameter. Westerly moisture dominated summer precipitation in Yinchuan Plain, while light, moderate, and heavy rains were additionally influenced by terrestrial evaporation vapor, Atlantic Ocean vapor, and Pacific Ocean vapor, respectively. Potential evaporation source areas exerted greater influence on light rain, primarily located in regions surrounding the study area and its northern, southern, and southeastern sectors. For moderate rain, potential sources were distributed around the study area and its northwestern and southeastern regions. For heavy rain, sources were concentrated around the study area and its southeastern region.

Keywords: precipitation grade; stable hydrogen and oxygen isotopes; water vapor source; vapor flux; potential contribution source area; Yinchuan Plain

Introduction

Under global climate warming, atmospheric circulation and water cycle processes have changed, substantially altering water vapor transport trajectories and causing spatiotemporal precipitation variations. Precipitation-related natural disasters such as droughts, floods, and waterlogging profoundly impact ecological construction and socioeconomic development. As precipitation plays a central role in maintaining groundwater levels and ecosystem stability, and given that Northwest China represents one of the country's most water-scarce regions, the area has experienced a gradual warm-wet climate transition in recent years with increasing extreme precipitation events that significantly affect the regional ecological environment. Therefore, understanding precipitation moisture sources and their relative contributions is crucial in regional ecohydrological research.

Hydrogen and oxygen stable isotopes (δ^{18}O and δD) exist throughout the water cycle and are highly sensitive to environmental changes across various timescales, making them widely applicable as tracers. Due to differing meteorological conditions and geographic factors, precipitation isotopic composition varies regionally, prompting numerous studies in China' s northwest arid regions, eastern monsoon regions, and the Tibetan Plateau that have examined spatiotemporal heterogeneity and seasonal variation mechanisms of precipitation isotopes along with differences in moisture sources among regions.

As a typical arid region in China, Northwest China exhibits complex precipitation moisture sources. Previous research has found that precipitation isotopes in this region show significant seasonal variation, with the westerly belt serving as the primary moisture source while also being influenced by monsoons and polar air masses. However, most studies have focused on seasonal or annual scales or heavy precipitation events in the Tianshan Mountains and Hexi Corridor, with limited research on Qinghai and Ningxia regions. Furthermore, few studies have investigated stable isotope characteristics and source differences across varied precipitation grades.

Water vapor transport forms the foundation of regional water cycle research, and water cycle conditions are vital for ecological environment evolution in the Yellow River Basin. Identifying moisture sources for different precipitation grades helps understand hydrological connections between target and contributing regions, representing a key to improving extreme precipitation forecasting and meteorological disaster prediction. With global warming and recent La Niña events intensifying atmospheric circulation anomalies, atmospheric moisture increases by approximately 7% per 1°C of global temperature rise. Located at the boundary between monsoon and non-monsoon climates and within China' s northern agro-pastoral ecotone, Yinchuan Plain' s special geographic position makes it particularly sensitive to climate change. How local moisture transport pathways change accordingly and whether potential evaporation source regions shift with precipitation intensity remain unanswered questions.

This study, based on precipitation event samples from Yinchuan Plain during May-October 2018-2020, analyzes stable isotope composition characteristics and secondary evaporation effects across precipitation grades. Combining backward trajectory modeling, water vapor flux divergence, and Potential Source Contribution Function (PSCF) analysis, we reveal moisture sources and potential evaporation source regions for different precipitation grades, explore varied moisture transport mechanisms, and provide scientific support for ecological protection and high-quality development in the Yellow River Basin.

1.1 Study Area Overview

Yinchuan Plain (35°27 -39°25 N, 105°20 -106°22 E) is located in the inland arid region of Northwest China, far from the ocean, with a temperate continental climate. The multi-year average temperature is 8.8°C, average annual precipitation is 209.7 mm, and the aridity index ranges from 4.8 to 8.5. Precipitation distribution is uneven, with annual precipitation on surrounding mountains reaching 1000-1550 mm. The Helan Mountains to the northwest weaken cold air from the northwest, block humid southeast monsoons, and restrain the eastward expansion of the Tengger Desert. Due to its special geographic location, the region experiences complex climate conditions and fragile ecological environments, with scarce precipitation concentrated mainly in the summer half-year and infrequent heavy precipitation events.

According to the Precipitation Intensity Grade Classification Standard (inland section) issued by the China Meteorological Administration, precipitation was classified into three grades: light rain (daily precipitation 0.1-9.9 mm), moderate rain (10-24.9 mm), and heavy rain (25-50 mm). The sampling point was located at Ningxia University in Yinchuan City, Ningxia Hui Autonomous Region [Figure 1: see original paper].

1.2 Sample Collection and Experimental Analysis

During the summer half-years (May-October) of 2018-2020, three standard rain gauges were placed in open areas on the Ningxia University campus. Precipitation samples were collected at 14:00, 20:00, and 02:00 (Beijing time) during rainfall events. Samples from each gauge were combined, immediately transferred to cryovials, sealed with Parafilm, and labeled with sampling time, location, and other relevant information. Samples were stored at -20°C for later analysis, yielding 87 valid samples. Meteorological data including temperature, precipitation amount, and relative humidity were obtained from the China Meteorological Data Network (https://data.cma.cn).

Hydrogen and oxygen stable isotope characteristics (δ^{18}O and δD) were measured using a Los Gatos Research DLT-100 liquid water isotope analyzer with measurement precisions of \$±\$0.5‰ for δ^{18}O and \$±\$0.3‰ for δD. Samples were filtered through 0.45 m membranes, and isotopic compositions were calibrated using the manufacturer' s spectral analysis software. Stable isotope values were calculated using the formula:

$$\delta = \frac{R_{\text{sample}} - R_{\text{VSMOW}}}{R_{\text{VSMOW}}} \times 1000‰$$

where R_{sample} and R_{VSMOW} represent the ratio of heavy to light isotope abundances in the precipitation sample and Vienna Standard Mean Ocean Water (VSMOW), respectively.

Deuterium excess (d-excess) traces moisture sources and pathways and was calculated as:

$$d\text{-excess} = \delta D - 8 \times \delta^{18}O$$

Daily isotopic values in precipitation were converted from event-based values using precipitation-weighted averaging:

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

where δ_{pw} is the precipitation-weighted average isotopic value, P_i is precipitation amount for event i, and δ_i is the corresponding stable isotope ratio.

1.3 Methods

1.3.1 Backward Trajectory Model The Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model was used to trace moisture sources. With the sampling point as the trajectory endpoint, 72-hour backward trajectories were simulated at 6-hour intervals (02:00, 08:00, 14:00, 20:00 Beijing time) at 1000 m height. Model data were obtained from the NCEP Global Data Assimilation System (GDAS) with 2.5°\$×\$2.5° spatial resolution.

1.3.2 Water Vapor Flux and Divergence Water vapor flux data from NCEP/NCAR reanalysis (2.5°\$×\$2.5° horizontal resolution) were used to verify moisture transport trajectories. While vapor flux magnitude and direction indicate moisture sources, precipitation grade correlates closely with vapor flux divergence. Positive divergence indicates vapor divergence, while negative values indicate convergence, with more negative values representing stronger convergence favorable for precipitation. The reanalysis data included temperature, geopotential height, relative humidity, specific humidity, and wind fields at 17 vertical levels.

1.3.3 Potential Source Contribution Function The Potential Source Contribution Function (PSCF) is a conditional probability-based method for qualitatively identifying potential pollution sources. By combining air mass trajectories with associated parameter values (e.g., water vapor d-excess), it identifies potential evaporation source locations. The PSCF value for grid cell (i,j) is calculated as:

$$\mathrm{PSCF}_{ij} = \frac{m_{ij}}{n_{ij}}$$

where n_{ij} is the total number of trajectory endpoints passing through grid cell (i,j) and m_{ij} is the number of endpoints with water vapor d-excess values exceeding the threshold. Thresholds were set at the 75th percentile of d-excess values for light, moderate, and heavy rains.

To reduce uncertainty in grid cells with small n_{ij}, a weighting function $W(n_{ij})$ was applied:

$$W_{ij} = \begin{cases} 1.0 & \text{if } n_{ij} > 80 \\ 0.7 & \text{if } 20 < n_{ij} \leq 80 \\ 0.4 & \text{if } 10 < n_{ij} \leq 20 \\ 0.2 & \text{if } n_{ij} \leq 10 \end{cases}$$

The weighted PSCF (WPSCF) was then calculated as:

$$\mathrm{WPSCF}_{ij} = W_{ij} \times \mathrm{PSCF}_{ij}$$

2.1 Characteristics of Stable Isotopes in Different Precipitation Grades

During the study period, atmospheric precipitation δD and $\delta^{18}O$ showed large variations, ranging from -152.53‰ to -5.93‰ and -20.31‰ to +4.31‰, respectively, with precipitation-weighted averages of -57.03‰ ± 27.03‰ and -7.37‰ ± 4.31‰. Maximum values appeared in May, while minimum values occurred in August. The weighted average $\delta^{18}O$ was higher than the national average. Light rain showed the largest isotopic variation range, while moderate rain showed the smallest, with stable isotope values becoming progressively depleted as precipitation grade increased.

Summer half-year d-excess ranged from -22.71‰ to 27.91‰, with a precipitation-weighted average of 13.91‰, smaller than the national average. By precipitation grade, light rain showed the largest d-excess variation range, while heavy rain showed the smallest. Light rain d-excess was negative, while moderate and heavy rains were positive, with weighted average d-excess values of 9.59‰ ± 4.59‰ for moderate rain and 15.16‰ ± 7.37‰ for heavy rain.

2.2 Local Meteoric Water Line

Linear regression of precipitation samples yielded the local meteoric water line (LMWL): $\delta D = 5.81\delta^{18}O - 10.85$ ($R^2 = 0.85$, $p < 0.05$). Its slope and intercept were lower than those of the eastern Loess Plateau and Dunhuang Basin, indicating strong below-cloud evaporation. The slope and intercept increased with precipitation amount, rising from 5.81 (light rain) to 6.87 (heavy rain), while intercept increased from -10.85 to -1.23, demonstrating that light rain events experienced more significant below-cloud secondary evaporation .

2.3 Factors Influencing Below-Cloud Secondary Evaporation

With increasing temperature, $\delta^{18}O$ first increased then decreased, while evaporation residue ratio (f) and d-excess first decreased then increased, indicating enhanced below-cloud evaporation at 0–20°C. Relative humidity significantly affected secondary evaporation: as humidity decreased, $\delta^{18}O$ gradually decreased while f and d-excess increased, showing stronger evaporation under drier conditions. When precipitation increased from 0–10 mm, $\delta^{18}O$ decreased while f and d-excess increased, indicating enhanced evaporation. For raindrop diameters of 0.6–0.8 mm, f was smallest and evaporation strongest; for 0.8–1.5 mm, f increased with reduced evaporation .

2.4 Analysis

2.4.1 Cluster Analysis of Precipitation Moisture Transport Pathways and Water Vapor Flux Variation Different precipitation grades showed consistent moisture flux directions from two sources: westerly vapor and southwest vapor extending from southwest to northeast. With increasing precipitation grade, the range and intensity of high-value centers expanded. Water vapor flux divergence analysis revealed that Yinchuan Plain was a moisture convergence zone for all precipitation grades, with negative divergence values decreasing as precipitation grade increased, indicating a positive correlation between convergence intensity and rainfall intensity—stronger convergence favors heavy precipitation events.

Cluster analysis of 72-hour backward trajectories at 1000 m height showed varying moisture source contributions across precipitation grades. Light rain [Figure 3a: see original paper] had two main sources: (1) vapor from Eastern Europe and Central Asia transported eastward by westerlies (68.05%), and (2) terrestrial evaporation vapor from East Asia and Mongolia (31.95%). Moderate rain [Figure 3b: see original paper] had three sources: westerly vapor from Central Asia (35.7%), Atlantic Ocean vapor (14.29%), and East Asian terrestrial evaporation vapor (41.67%). Heavy rain [Figure 3c: see original paper] included westerly vapor from Central Asia (37.50%), Pacific Ocean vapor from the southeast (20.8%), and vapor from the Tibetan Plateau (20.8%). All grades were controlled by westerly vapor, with oceanic vapor proportion increasing with precipitation grade.

2.4.2 Potential Evaporation Source Analysis WPSCF analysis revealed that light rain events [Figure 5a: see original paper] had numerous high-value zones widely distributed around the study area and in southern Inner Mongolia and southwestern Henan—regions with dry climates and strong evaporation that constitute major potential evaporation sources. Moderate rain events [Figure 5b: see original paper] showed more concentrated potential source zones around the study area and near the Mongolian Plateau, extending southeastward in bands. Heavy rain events [Figure 5c: see original paper] displayed markedly reduced high-value areas, with only scattered points around the study area and its southeastern region. Overall, potential evaporation sources exerted greater influence on light rain, while moderate and heavy rains were primarily affected by external moisture transport, with sources mainly distributed around the study area and in northwestern and southeastern regions, indicating these areas have high local recycled moisture that can supply precipitation in Yinchuan Plain.

3.1 Secondary Evaporation Effects on Atmospheric Stable Isotopes

Below-cloud secondary evaporation alters precipitation stable isotope characteristics and the slope/intercept of meteoric water lines under different meteorological conditions. The LMWL slope and intercept in Yinchuan Plain were lower than those in many northern Chinese regions, reflecting the region’ s dry climate and strong below-cloud evaporation that causes non-equilibrium fractionation and heavy isotope enrichment. Secondary evaporation was more pronounced in light rain events than in moderate and heavy rains, being strongest when precipitation was 0–2 mm. Smaller raindrops fall through drier air, experiencing stronger isotopic fractionation from non-equilibrium evaporation, whereas larger raindrops fall through more saturated air with weaker fractionation. During heavy or continuous precipitation, atmospheric moisture gradually saturates, reducing below-cloud evaporation. Beyond precipitation amount, temperature, relative humidity, and raindrop diameter also affect secondary evaporation. Temperature correlates positively with evaporation, but when exceeding 20°C, precipitation amount masks temperature effects, causing isotopic depletion. Relative humidity, precipitation amount, and raindrop diameter correlate negatively with evaporation—when these parameters are small, $\delta^{18}O$ is small and evaporation is strong, consistent with findings from Liu et al. and Xiao et al.

3.2 Regional Precipitation Water Vapor Transport Mechanisms

Located at the northern edge of the East Asian summer monsoon, Yinchuan Plain’ s climate is primarily controlled by westerly circulation with year-round westerly moisture transport. However, this study found Pacific Ocean vapor from the southeast in heavy rainfall events. Recent weakening of the East Asian summer monsoon, accompanied by westward extension of the Western Pacific Subtropical High and increased Mongolian anticyclone activity, has promoted westward transport of Pacific summer moisture, causing multiple heavy rainfall events in the study area. For example, an extreme heavy rainfall event on July 23, 2018, in Xixia District caused urban waterlogging. This event resulted from Typhoon "Ampil"making landfall along the southeast coast, with the subtropical high extending westward and northward, continuously transporting moisture to northwestern regions and creating atmospheric instability.

Tropical maritime air masses typically have relatively depleted heavy isotope compositions, lowering regional $\delta^{18}O$ values. Light rain events controlled by westerly air masses experienced strong evaporation with heavy isotope enrichment and higher $\delta^{18}O$ values. Combined with d-excess variations and backward trajectories, light rain moisture sources included not only westerly vapor but also terrestrial evaporation vapor—mostly short-distance local recycled moisture with high temperatures and low humidity, resulting in significantly low d-excess values. Chen et al. found that ocean-transported precipitation has low d-excess values that increase with decreasing relative humidity at moisture sources. In this study, heavy rain had lower d-excess than moderate rain; heavy rain contained Pacific moisture from the southeast with abundant near-surface moisture, high humidity, and slow evaporation, while moderate rain' s Atlantic moisture had longer transport paths and less moisture due to mountain blocking, causing isotopic depletion and higher d-excess values.

Comparing backward trajectory and water vapor flux methods revealed that trajectory analysis showed no southwest air masses, while vapor flux analysis indicated Bengal Bay moisture influence. This discrepancy arises because the Tibetan Plateau blocks Indian Ocean moisture northward movement; when the summer monsoon is strong, Indian Ocean moisture moves northeastward along the plateau edge into the study area, bringing humid air.

4 Conclusions

1) Stable isotope values in Yinchuan Plain summer half-year precipitation were higher than national averages. Across precipitation grades, isotope values became progressively depleted with increasing precipitation magnitude. d-excess values were lower than the national average, being negative for light rain and positive for moderate and heavy rains.

2) The LMWL slope and intercept decreased with increasing precipitation grade. Secondary evaporation effects intensified with rising temperature but weakened with increasing precipitation amount, relative humidity, and raindrop diameter.

3) Summer half-year precipitation moisture sources were primarily controlled by westerly air masses, with differences among precipitation grades. Besides westerly vapor, light rain included high-latitude terrestrial evaporation vapor, moderate rain included Central Asian terrestrial evaporation and Atlantic Ocean vapor, and heavy rain included southeastern Pacific Ocean vapor. Potential evaporation sources for light rain were distributed

around the study area and its northern, southern, and southeastern regions; for moderate rain, around the study area and its northwestern and southeastern regions; and for heavy rain, around the study area and its southeastern region.

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