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Temporal Scale Effects of Stable Hydrogen and Oxygen Isotopes in Precipitation and Water Vapor Sources in the Yinchuan Plain Postprint

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Date: 2022-01-21T00:00:00+00:00

Abstract

To reveal the temporal scale effects of precipitation stable isotopes and water vapor sources in the Yinchuan Plain, backward trajectory model cluster analysis, Potential Source Contribution Function (PSCF) analysis, and Concentration Weighted Trajectory (CWT) analysis were employed to analyze water vapor sources and potential evaporation source regions. The results show that: (1) The composition of hydrogen and oxygen stable isotopes in precipitation in the Yinchuan Plain exhibits significant seasonal variation; the composition of hydrogen and oxygen stable isotopes in winter half-year precipitation (-38.6‰$±51.6‰and −4.5‰±5.2‰)issignificantlymorepositivethanthatinsummerhalf−yearprecipitation(−40.9‰±17.7‰and−5.7‰±$3.0‰); under different time periods, the Local Meteoric Water Line (LMWL) shows significant differences, with the slope and intercept of the LMWL in the summer half-year (5.43, -9.71) being lower than those in the winter half-year (9.10, 5.08) and those of the annual LMWL in the Yinchuan Plain (6.79, -2.79). (2) In the annual, summer half-year, and winter half-year periods, the temperature effect of $ 18Oinprecipitationissignificant,withthetemperatureeffectsbeing(0.473±0.210)‰·°C{-1},(0.258±0.037)‰·°C{-1},and(0.211±0.031)‰·°C^{-1}$, respectively, while the precipitation amount effect is not significant. (3) In both the summer half-year and winter half-year, the water vapor sources for precipitation in the study area are mainly westerly water vapor, while also being influenced by local evaporation water vapor. In the summer half-year, water vapor evaporation source regions are mainly distributed in the areas surrounding the study area and in the west, southwest, and south; in the winter half-year, they are mainly distributed in the areas surrounding the study area and in the west. The research results can provide a theoretical basis for method selection in using stable isotope technology to identify water vapor sources in arid regions.

Full Text

Time Scale Effect of Hydrogen and Oxygen Stable Isotopes in Precipitation and Water Vapor Sources in the Yinchuan Plain

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Abstract

To reveal the time scale effect of stable isotopes in precipitation and water vapor sources in the Yinchuan Plain, backward trajectory model clustering analysis, Potential Source Contribution Function (PSCF), and Concentration Weighted Trajectory (CWT) analysis were employed to resolve water vapor sources and potential evaporation source areas. The results demonstrated that: (1) The hydrogen-oxygen stable isotope composition of precipitation in the Yinchuan Plain exhibited pronounced seasonal variations, with winter half-year values (δD = −38.6‰ ± 51.6‰, δ^{18}O = −4.5‰ ± 5.2‰) significantly more positive than summer half-year values (δD = −40.9‰ ± 17.7‰, δ^{18}O = −5.7‰ ± 3.0‰). The slope and intercept of the Local Meteoric Water Line (LMWL) also showed significant differences across time periods, with summer half-year values (5.43, −9.71) lower than winter half-year values (9.10, 5.08) and whole-year values (6.79, −2.79). (2) The temperature effect was significant during all three periods, with coefficients of (0.473 ± 0.210) ‰ · $°C^{-1}$, (0.258 ± 0.037) ‰ · $°C^{-1}$, and (0.211 ± 0.031) ‰ · $°C^{-1}$ for the entire year, summer half-year, and winter half-year, respectively, while the precipitation effect remained insignificant. (3) During both summer and winter half-years, precipitation moisture in the study area originated primarily from westerly vapor, supplemented by local evaporative vapor. In the summer half-year, potential evaporative source areas were mainly distributed in the surrounding region and the western, southwestern, and southern sectors; during the winter half-year, they were concentrated in the surrounding region and western areas. These findings provide a theoretical basis for selecting appropriate methods to identify water vapor sources using stable isotope techniques in arid regions.

Keywords: atmospheric precipitation; stable isotope effect; water vapor source; potential evaporation source; different time scales; Yinchuan Plain

1. Study Area Overview

The Yinchuan Plain is situated on the western side of the central Loess Plateau [Figure 1: see original paper]. Characterized by a temperate continental semi-arid climate, the region has a multi-year average temperature of 8.8 °C, multi-year average precipitation of 209.7 mm, and multi-year average evaporation of 1584.4 mm as measured by a lysimeter. Precipitation shows strong intra-annual variability, concentrated primarily in July–September, accounting for approximately 72.4% of the multi-year average (data from the China Meteorological Data Network hourly observations). Water resources constitute a critical factor influencing and constraining high-quality development and ecological construction in this northwestern arid region of China. Precipitation represents a vital component of the water cycle, and investigating the temporal scale effects of stable isotopes in precipitation can effectively trace regional water vapor sources and quantitatively elucidate precipitation distribution within the water cycle, which is essential for understanding local water cycle processes.

Previous studies on stable isotopes in Yinchuan Plain precipitation, primarily based on monthly average data from the IAEA/WMO monitoring network at Yinchuan station, have been limited by station density and data timeliness, leaving knowledge gaps regarding environmental effects and water vapor sources. Moreover, as the region lies on the edge of the monsoon zone in northwestern China, the characteristics of hydrogen-oxygen stable isotopes differ from other arid areas in the northwest, and the evaporative source areas remain unclear. This study addresses these gaps by analyzing event-scale precipitation samples collected at Yinchuan and Lingwu stations in the Yinchuan Plain, examining variations in stable isotopes, Local Meteoric Water Lines (LMWL), temperature and precipitation effects across different time periods (entire year, summer half-year, and winter half-year), and investigating water vapor sources and potential evaporative source areas to provide references for future studies on local water cycle processes in northwestern arid regions and to offer viable methods for water vapor source identification.

2. Data and Methods

2.1 Data Collection

Event-scale precipitation samples were collected at two monitoring sites: Ningxia University Helan Mountain Campus in Yinchuan City (38°30 05 N, 106°08 34 E, elevation 1130 m) and Baijitan National Nature Reserve in Lingwu City (38°03 34 N, 106°22 03 E, elevation 1120 m) [Figure 1: see original paper]. Following the "Collection and Preservation of Atmospheric Precipitation Samples" standard (GB/T13580.2-1992), sampling was conducted twice daily at 08:00 and 20:00 on precipitation days, with the sum recorded as daily precipitation for events $ $0.1 mm. Detailed sample information is provided in .

At the Yinchuan site, to minimize contamination from buildings and other sources, three standard rain gauges (20 cm diameter) were placed on a rooftop, each equipped with a funnel connected to the gauge and a ping-pong ball in the funnel to prevent evaporation. At the Lingwu site, standard rain gauges were placed in an open, forest-free area. Liquid precipitation was immediately transferred to 30 mL polyethylene bottles sealed with Parafilm; snow samples were first placed in sealed bags, allowed to melt completely at room temperature, then transferred to 30 mL bottles. All samples were refrigerated at approximately 4 °C after filtration through 0.45 m mixed cellulose membranes.

Stable isotope compositions were measured using a Los Gatos Research DLT-100 liquid water isotope analyzer with measurement precisions of 0.5‰ for δD and 0.1‰ for δ^{18}O. Results are expressed as per mil deviations relative to Vienna Standard Mean Ocean Water (VSMOW):

δ = (R_{sample}/R_{VSMOW} - 1) × 1000‰

where R represents the ratio of heavy to light isotope abundances. Deuterium excess (d-excess = δD - 8 × δ^{18}O) traces precipitation moisture sources. Daily vapor isotope values were calculated from event precipitation values using:

δ^{18}O_{PV} = δ^{18}O_P - 10^{-3} × ^{18}O
δD_{PV} = δD_P - 10^{-3} × D

where represents equilibrium fractionation coefficients between precipitation and vapor, related to temperature (T, in °C) by:

 ^{18}O = 1.137\$$\times10^{\{3\}/T}$\{2\}\$ - 0.4156\$$\times10^{\{3\}/T - 2.0667\varepsilon D = 24.844\times10}\{3\}/T$^\{2\}\$ - 52.612\$×10^\{3\}\$/T - 76.248

Precipitation isotope weighted averages were calculated as:

δ = Σ(δ_i × P_i)/ΣP_i

where δ_i and P_i are the isotope value and precipitation amount for event i, respectively.

2.2 Data Sources and Processing

Meteorological data (hourly observations from Yinchuan and Lingwu stations) were obtained from the China Meteorological Data Network (https://data.cma.cn) with quality control ensuring data availability rates exceeding 99.9%. Air mass backward trajectory data utilized global reanalysis data from the National Centers for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR) with 2.5° × 2.5° spatial resolution.

2.3 Analytical Methods

2.3.1 Relationship between δ^{18}O and Temperature/Precipitation The temperature effect describes positive correlation between stable isotopes in precipitation and temperature, while the precipitation effect describes negative correlation with increasing precipitation amount. Partial correlation coefficients and P-values were applied to examine relationships between δ^{18}O and these variables. When both effects coexist, the temperature effect represents the first derivative of δ^{18}O with respect to temperature while holding precipitation constant, and vice versa for the precipitation effect, following the binary linear model:

$\delta^{18}O = a_0 + a_1T + a_2P +$

where a_1 and a_2 (‰ · °C^{-1} and ‰ · mm^{-1}) represent temperature and precipitation effects, respectively; a_0 is a constant; T is mean temperature (°C); P is precipitation amount (mm); and is random error. Analysis of variance and F-tests assessed regression significance, while t-tests evaluated coefficients. Partial determination coefficients quantified each effect’ s contribution.

2.3.2 Backward Trajectory Simulation of Precipitation Moisture Sources The TrajStat software, widely applied in moisture transport studies, simulated backward trajectories for precipitation days at Yinchuan station. Trajectories were calculated at 6-hour intervals (local times 08:00, 14:00, 20:00, 02:00) with starting heights of 1500 m, 2500 m, and 5000 m. A 240-hour backtrack duration was used based on the ~10-day average residence time of tropospheric moisture. The Angle Distance algorithm clustered trajectories to identify dominant moisture transport pathways for different periods.

2.3.3 Potential Source Contribution Function (PSCF) PSCF identifies potential source areas based on conditional probability. The study area was divided into 0.5° × 0.5° grids. For each grid cell (i,j), PSCF is defined as:

PSCF_{ij} = m_{ij}/n_{ij}

where n_{ij} is the total number of trajectory nodes in the grid, and m_{ij} is the number of nodes with water vapor d-excess values exceeding the threshold (set as the average d-excess for summer half-year and winter half-year separately). Higher PSCF values indicate stronger evaporation from the underlying surface. To reduce uncertainty when n_{ij} is small, a weighting function W_{ij} was applied:

W_{ij} = 1.00, n_{ij} > 80
0.70, 20 < n_{ij} ≤ 80
0.42, 10 < n_{ij} ≤ 20
0.05, n_{ij} ≤ 10

The weighted PSCF (WPSCF_{ij}) = W_{ij} × PSCF_{ij}.

2.3.4 Concentration Weighted Trajectory (CWT) Analysis While PSCF indicates the proportion of trajectories exceeding d-excess thresholds, CWT quantifies relative contributions of potential evaporative sources to target grid precipitation. The average weighted d-excess value for each grid reflects the influence magnitude:

CWT_{ij} = Σ(k=1 to N) C_k × α*{ijk} / Σ(k=1 to N)* α{ijk}

where C_k is the d-excess value (‰) at the study site for trajectory k, α*{ijk} is the residence time of trajectory k in grid (i,j), and N is the total number of trajectories. The same weighting function W*{ij} was applied to obtain WCWT_{ij} = W_{ij} × CWT_{ij}.

3. Results

3.1 Temporal Variation Characteristics of Stable Isotopes in Precipitation

Daily δD values ranged from $-152.6‰$ to 31.8‰ with a precipitation-weighted average of $-40.9‰ \pm 17.7‰$, while δ^{18}O ranged from $-19.6‰$ to 4.2‰ with a weighted average of $-5.7‰ \pm 3.0‰$. The d-excess varied from $-17.0‰$ to 21.8‰, averaging $4.7‰ \pm 4.5‰$. Precipitation isotopes showed clear seasonal patterns, with winter half-year weighted averages (δD = $-38.6‰ \pm 51.6‰$, δ^{18}O = $-4.5‰ \pm 5.2‰$) more positive than summer half-year values. Correspondingly, winter half-year d-excess ($6.8‰ \pm 7.1‰$) was significantly higher than summer half-year values ($3.2‰ \pm 3.0‰$). During summer, long-distance moisture transport depleted isotopes, while winter moisture from dry, evaporative mid-high latitude continental air masses with minimal en-route precipitation enriched isotopes. Notably, Yinchuan station showed more positive δ^{18}O values than Lingwu station in both seasons, while d-excess patterns were reversed, with Lingwu exhibiting higher values [Figure 2: see original paper].

3.2 Characteristics of the Local Meteoric Water Line

The annual LMWL for Yinchuan Plain ($\delta D = 6.79\delta^{18}O - 2.79$) had lower slope and intercept than the Global Meteoric Water Line (GMWL: $\delta D = 8\delta^{18}O + 10$), reflecting intense sub-cloud evaporation in this inland arid region causing non-equilibrium fractionation and heavy isotope enrichment. Winter half-year LMWL slope and intercept exceeded summer half-year values , indicating stronger sub-cloud evaporation effects during summer. Seasonal differences between stations were more pronounced in winter, likely due to varying evaporation intensities and local moisture recycling [Figure 3: see original paper].

3.3 Temperature and Precipitation Effects

Significant positive correlations existed between δ^{18}O and temperature during the entire year and summer half-year, with temperature effects of (0.473 ± 0.210) ‰·°C^{-1} and (0.258 ± 0.037) ‰·°C^{-1}, respectively [TABLE:3, TABLE:4]. The summer half-year effect exceeded the annual average. No significant temperature correlation was observed in winter half-year, possibly due to dominant mid-high latitude continental air masses. Precipitation effects were insignificant across all periods, likely because the region' s continental climate, strong westerly influence, and orographic blocking of Pacific and Indian Ocean moisture weaken monsoon impacts. Partial correlation analysis confirmed that temperature effects remained significant when controlling for precipitation, while precipitation effects were negligible when controlling for temperature, consistent with previous findings for Ningxia and northwestern China.

3.4 Water Vapor Source Analysis

3.4.1 Backward Trajectory Clustering During summer half-year, westerly pathways dominated at all three heights, accounting for 79.60% of moisture transport at 1500 m, with local evaporative moisture contributing 20.40% [Figure 4: see original paper]. At 2500 m and 5000 m, westerly mid-distance transport prevailed. In winter half-year, westerly pathways were even more dominant, representing 92.73% at 1500 m, with local evaporative moisture dropping to 7.27%. At higher altitudes, long-distance westerly transport increased while local contributions decreased further.

3.4.2 PSCF Analysis Summer half-year WPSCF values >0.4 were concentrated in the surrounding region, west, southwest, and south [Figure 5: see original paper]. At 1500 m, high-value areas covered the southwestern and eastern regions. At 2500 m, the high-value area shrank and migrated southward, concentrating around the study area and western regions. At 5000 m, the area continued shrinking, focusing on the surrounding and western regions, suggesting reduced influence of westerly transport at higher altitudes.

Winter half-year WPSCF patterns showed high values (>0.4) primarily in the surrounding region and west. At 1500 m, the high-value area was extensive, covering surrounding areas and extending westward. At 2500 m, the area contracted and shifted southward, concentrating around the study area. At 5000 m, it further shrank and dispersed, mainly in surrounding and western regions, indicating westerly vapor' s dominant winter influence and reduced local evaporation compared to summer.

3.4.3 CWT Analysis Summer half-year WCWT values $>0.5 \times 10^{-3}$ were distributed in surrounding areas, west, and east at 1500 m [Figure 6: see original paper]. At 2500 m, the high-value area ($>0.5 \times 10^{-3}$) shrank significantly to the southwest, while western areas $>0.4 \times 10^{-3}$ also contracted. At 5000 m, no distinct high-value areas appeared.

Winter half-year WCWT values $>0.5 \times 10^{-3}$ were concentrated in surrounding areas at 1500 m, with southwestern contributions. At 2500 m, high-value areas increased and concentrated in the west, with secondary eastern contributions. At 5000 m, areas $>0.5 \times 10^{-3}$ shrank and dispersed, mainly in surrounding regions, with southwestern contributions.

4. Conclusions

This study investigated environmental effects, water vapor sources, potential evaporative source areas, and their contributions for stable isotopes in Yinchuan Plain precipitation across different time periods, yielding three main conclusions:

1) Hydrogen-oxygen stable isotopes in Yinchuan Plain precipitation showed significant seasonal variation, with winter half-year values (δD = $-38.6‰$ ± $51.6‰$, δ^{18}O = $-4.5‰$ ± $5.2‰$) substantially more positive than summer half-year values (δD = $-40.9‰$ ± $17.7‰$, δ^{18}O = $-5.7‰$ ± $3.0‰$). LMWL slope and intercept differed significantly across the entire year, summer half-year, and winter half-year. After controlling for precipitation, δ^{18}O maintained significant positive correlation with temperature across all three periods, with temperature effects of (0.473 ± 0.210) $‰\cdot°C^{-1}$, (0.258 ± 0.037) $‰\cdot°C^{-1}$, and (0.211 ± 0.031) $‰\cdot°C^{-1}$, respectively. After controlling for temperature, δ^{18}O showed positive correlation with precipitation, but the precipitation effect was not significant.
2) During both summer and winter half-years, precipitation was significantly influenced by westerly vapor and local evaporative vapor. In summer, potential evaporative source areas were mainly located in surrounding regions and the western, southwestern, and southern sectors. In winter, they were concentrated in surrounding areas and the west.

These findings provide theoretical guidance for selecting appropriate stable isotope techniques to identify water vapor sources in arid regions.

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