Stable Hydrogen and Oxygen Isotope Characteristics of Precipitation and Water Vapor Sources in the Altai Mountains (Postprint)

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Date: 2022-08-08T00:00:00+00:00

Abstract

The Altai Mountains span central Eurasia and constitute a key region for research on mid-latitude westerly belt climate. Using monitoring data from four stations in the Altai Mountains region, this study investigates the intra-annual variation characteristics of stable hydrogen and oxygen isotopes in precipitation and the local meteoric water line equation, analyzes the temperature effect of precipitation isotopes, and explores moisture sources using backward trajectories. The results indicate: (1) Precipitation isotope ratios at various stations in the Altai Mountains show a seasonal pattern of higher values in summer and lower values in winter, with southern stations exhibiting greater seasonal differences than northern stations; except for Novosibirsk, most stations display lower deuterium excess values in summer and higher values in winter. (2) Except for Novosibirsk, the slope and intercept of the local meteoric water line equation at most stations in the study area are lower than the global average. (3) Precipitation isotopes at all stations exhibit a significant temperature effect, manifested in both seasonal variation and spatial distribution. (4) Backward trajectories indicate that the study area is influenced by westerly moisture, polar moisture, and proximal moisture pathways, with more northerly stations potentially being more affected by polar moisture pathways. These findings help clarify the hydroclimatic information reflected by spatiotemporal variations of precipitation isotopes in different regions of the Altai Mountains and provide a reference for research on atmospheric water cycle and climate change in this region.

Full Text

Stable Hydrogen and Oxygen Isotopes in Precipitation and Water Vapor Sources in the Altay Mountains

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Abstract: The Altay Mountains, stretching across the central Eurasian continent, represent a key region for climate research in the mid-latitude westerly belt. Based on monitoring data from four stations across the Altay Mountains, this study investigates the intra-annual variation characteristics of stable hydrogen and oxygen isotopes in precipitation and establishes local meteoric water line equations. The temperature effect on precipitation isotopes is analyzed, and water vapor sources are examined using backward trajectory analysis. The results demonstrate that isotope ratios in precipitation exhibit higher values in summer and lower values in winter, with more pronounced seasonal differences at southern stations compared to northern stations. Deuterium excess values are generally lower in summer and higher in winter at most stations, except for Novosibirsk. The slopes and intercepts of local meteoric water lines are below global averages at most stations, with the exception of Novosibirsk. A clear temperature effect is observed in precipitation isotopes, manifested in both seasonal variations and spatial distribution patterns. Backward trajectory analysis reveals that the study area is influenced by three primary moisture pathways: westerly transport, polar air masses, and locally recycled vapor, with northern stations potentially experiencing greater influence from polar moisture pathways. These findings enhance understanding of hydrological and climatic information encoded in precipitation isotopes across different regions of the Altay Mountains and provide a valuable reference for studies of atmospheric water cycling and climate change in this region.

Keywords: precipitation isotopes; backward trajectory; water vapor source; Altay Mountains

1 Introduction

Atmospheric precipitation constitutes a critical component of the water cycle and represents the primary input form of surface water resources [1]. Stable hydrogen and oxygen isotopes in precipitation serve as effective tracers for investigating hydrological processes including evaporation, condensation, and water vapor transport [2]. In the arid regions of Central Asia, mountain precipitation is not only an important source of regional water resources [3] but also a key focus for isotope monitoring studies [4]. Long-term monitoring in the Tianshan and Qilian Mountains has revealed significant seasonal differences in precipitation isotope ratios [5], with strong sub-cloud secondary evaporation further amplifying these seasonal variations [6]. In addition to westerly and monsoon circulations that may influence precipitation in these mountainous regions [7], local moisture recycling also contributes substantially to precipitation [8]. These isotope monitoring studies provide crucial foundations for understanding water cycling processes in the mountainous regions of Central Asia.

Among these mountain systems, the Altay Mountains, located at relatively high latitudes, are consistently influenced by westerly circulation and polar air masses, receiving substantial precipitation during winter and spring—a distinctive regional characteristic [9]. Over recent decades, the Altay Mountains have exhibited a clear warming trend, though precipitation changes vary between the northern and southern slopes [10]. Compared to the Tianshan and Qilian Mountains, modern isotope monitoring of precipitation in the Altay Mountains remains limited [11]. On the southern slopes within China, precipitation isotope monitoring has only been reported for Altay City [12], with most other studies comprising temporary short-term sampling [13]. The Altay Mountains extend over a long east-west transect, and different regions experience varying degrees of influence from westerly circulation and polar air masses. Currently, comparative studies of precipitation isotopes across different regions of the Altay Mountains are lacking.

To address this research gap, this study selected four stations across the Altay Mountains to analyze the intra-annual variation characteristics of stable hydrogen and oxygen isotopes in precipitation and establish local meteoric water lines. The temperature effect on precipitation isotopes is examined, and water vapor sources are analyzed using backward trajectory methods. The objective is to clarify the hydrological and climatic information reflected by stable isotopes in the Altay Mountains, providing a reference for studies of modern atmospheric water cycling and paleoclimate environmental reconstructions.

2 Data and Methods

2.1 Data Sources

2.1.1 Precipitation Isotope Observations The Altay Mountains are situated at the intersection of China, Kazakhstan, Russia, and Mongolia in central Eurasia, extending in a northwest-southeast orientation with a length of nearly 2000 km and exhibiting a pronounced continental climate. This study utilized stable hydrogen and oxygen isotope data from four stations across the Altay Mountains region , arranged from south to north as Takhin Tal (Mongolia), Altay (China), Zonalnoe (Russia), and Novosibirsk (Russia) [12, 14, 22, 24]. The study focused on intra-annual variation and spatial distribution patterns, analyzing multi-year monthly averages of precipitation isotopes. Isotope ratios are expressed as per mil (‰) deviations relative to Vienna Standard Mean Ocean

Water (VSMOW).

2.1.2 Precipitation Isotope Simulation Data To evaluate the applicability of global precipitation isotope simulation products in the study area, two common datasets were employed: the Online Isotopes in Precipitation Calculator (OIPC) version 3.2, released by the University of Utah with a spatial resolution of 5 $×5′, andtheRegionalizedCluster − basedWaterIsotopePrediction(RCWIP)version1.0, releasedbytheInternationalAtomicEnergyAgencywitha Both products include multi-year monthly average precipitation δ^{18}O and deuterium excess values.

2.1.3 Climate Grid Data Multi-year average climate data were obtained from the Climatic Research Unit (CRU) at the University of East Anglia, specifically the CRU TS4.03 dataset of global monthly mean surface climate variables [29], including temperature and precipitation at a resolution of 0.5°$×$0.5°.

2.2 Research Methods

Backward trajectory analysis was performed using the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model from the Air Resources Laboratory of the National Oceanic and Atmospheric Administration (NOAA) [30]. Daily Global Data Assimilation System (GDAS) data from the National Centers for Environmental Prediction (NCEP) served as input parameters for trajectory calculations, with a spatial resolution of 1°$×$1° [33]. Trajectories were calculated at 500 m above ground level as the precipitation height [31]. Starting times were set at 00:00, 06:00, 12:00, and 18:00 UTC daily, with 240 hours (10 days) as the backward tracking duration, using station locations as starting points. Cluster analysis was performed on monthly trajectories for each sampling year.

3 Results

3.1 Intra-Annual Variation of Precipitation Isotopes

The intra-annual variations of δ^{18}O, δ^{2}H, and deuterium excess (d) at each station are shown in [Figure 2: see original paper]. Monthly δ^{18}O values range from approximately -25.8‰ to -5.3‰ at Takhin Tal, -23.8‰ to -5.6‰ at Altay, -22.5‰ to -7.6‰ at Zonalnoe, and -24.1‰ to -11.1‰ at Novosibirsk. Precipitation-weighted averages are -12.1‰, -11.4‰, -13.5‰, and -17.3‰, respectively. All stations exhibit pronounced intra-annual variations, with higher values in summer and lower values in winter. Southern stations (Takhin Tal and Altay) show greater seasonal amplitude than northern stations (Zonalnoe and Novosibirsk). Except for Novosibirsk, monthly δ^{18}O values at Altay are generally higher than at other stations throughout the year.

Deuterium excess values, which indicate the influence of evaporation on precipitation processes [34], show distinct spatial patterns. Takhin Tal exhibits the lowest d values, ranging from -5.5‰ to 15.5‰ with a mean of 5.9‰—a pattern rarely observed in previous studies and likely attributable to strong sub-cloud evaporation in this extremely arid region at the western edge of the Mongolian Plateau. Altay shows d values between 1.5‰ and 25.8‰, averaging 13.0‰, slightly below the global average of ~10‰. Zonalnoe ranges from 3.5‰ to 22.5‰ (mean 11.4‰), also below the global average. Novosibirsk shows the highest d values (5.5–22.5‰, mean 15.5‰) and displays a unique autumn-high, winter-low pattern. The large intra-annual differences in d across stations likely reflect varying moisture sources and evaporation conditions in the Altay Mountains.

The applicability of global isotope simulation products was evaluated by comparing simulated and observed values . At most stations, both OIPC and RCWIP show higher R^2 values for $\delta^{18}O$ than for d, indicating better simulation of $\delta^{18}O$. RCWIP generally outperforms OIPC for $\delta^{18}O$, while OIPC performs better for d at Altay, Zonalnoe, and Novosibirsk. Simulation accuracy is poorest at Takhin Tal, the most arid station.

3.2 Meteoric Water Lines

Local meteoric water lines were established for each station [Figure 3: see original paper]: $\delta^2H = 7.40\delta^{18}O - 13.57$ ($R^2 = 0.98$, $p < 0.01$) for Takhin Tal; $\delta^2H = 7.74\delta^{18}O + 5.94$ ($R^2 = 0.93$, $p < 0.01$) for Altay; $\delta^2H = 7.37\delta^{18}O - 4.07$ ($R^2 = 0.99$, $p < 0.01$) for Zonalnoe; and $\delta^2H = 8.76\delta^{18}O + 24.1$ ($R^2 = 0.97$, $p < 0.01$) for Novosibirsk. The slope of the meteoric water line reflects evaporation conditions, with the global meteoric water line defined as $\delta^2H = 8\delta^{18}O + 10$ [35]. Slopes below the global average indicate arid conditions and significant sub-cloud evaporation [12]. Takhin Tal, Altay, and Zonalnoe all show slopes below the global average, suggesting pronounced evaporative effects during precipitation. Novosibirsk, with the highest latitude and lowest temperatures, shows a slope above the global average, indicating minimal evaporative influence. These results align with previous studies in the Tianshan, Kunlun, and Qilian Mountains, where slopes are generally at or below global values [11], reflecting the overall arid climate of Central Asia.

3.3 Temperature Effect on Precipitation Isotopes

Precipitation $\delta^{18}O$ shows a significant positive correlation with air temperature at all stations [Figure 4: see original paper], a phenomenon known as the temperature effect in isotope hydrology [34]. While temperature effects primarily occur at high latitudes on intra-annual scales, they are globally prevalent on spatial scales. Consistent with seasonal isotope variations, summer temperatures correspond to the highest isotope ratios, while winter temperatures correspond to the lowest. Spatially, temperature decreases with increasing latitude across the four stations, from Altay (highest mean temperature) to Novosibirsk (lowest). Correspondingly, precipitation $\delta^{18}O$ values are highest at Altay and lowest at

Novosibirsk. The temperature effect is thus evident in both seasonal and spatial patterns across the Altay Mountains.

3.4 Water Vapor Source Trajectory Analysis

Cluster analysis of backward trajectories for different seasons reveals three primary moisture sources affecting the Altay Mountains [Figure 5: see original paper]: westerly-transported maritime moisture with along-path supplementation, polar Arctic Ocean moisture, and locally evaporated moisture. The contribution of locally recycled moisture to precipitation is greater at Altay than at other stations, exceeding 50% annually and contributing to Altay' s relatively high mean isotope ratios. Northern stations are more influenced by polar moisture pathways, particularly during winter when westerly activity shifts southward.

Summer temperatures promote evaporation from continental water bodies, enriching westerly-transported moisture with heavy isotopes and enhancing sub-cloud evaporation, resulting in high summer isotope ratios. Conversely, winter conditions limit evaporation and sub-cloud effects, leading to isotope depletion. Spatially, the Altay Mountains' extensive east-west span obstructs both westerly and polar air masses, reducing precipitation in southern and eastern regions compared to northern and western areas. Polar air masses have minimal influence on southern precipitation, while locally recycled moisture contributes little to northern regions. Unlike the Tianshan and Qilian Mountains [11, 15], the Altay Mountains receive virtually no monsoonal influence.

4 Conclusions

Based on stable hydrogen and oxygen isotope data from four stations across the Altay Mountains, this study investigated precipitation isotope characteristics and moisture source pathways, yielding the following conclusions:

(1) Precipitation isotope ratios in the Altay Mountains show significant intra-annual variation, with higher values in summer and lower values in winter. Seasonal differences are more pronounced at southern stations than at northern stations. Deuterium excess values are generally lower in summer and higher in winter at most stations, except for Novosibirsk.

(2) Except for Novosibirsk, the slopes and intercepts of local meteoric water lines are below global averages, indicating substantial influence from sub-cloud evaporation under the region' s arid climate background. The temperature effect on precipitation isotopes is clearly evident in both seasonal and spatial patterns.

(3) Backward trajectory analysis indicates that the Altay Mountains are primarily influenced by westerly, polar, and locally recycled moisture pathways, with northern stations being more affected by polar moisture pathways.

These findings provide important insights into the hydrological and climatic information encoded in precipitation isotopes across the Altay Mountains and offer a valuable reference for research on atmospheric water cycling and climate change in the region.

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