Spatial Distribution Characteristics of Stable Isotopes in Alpine Precipitation in Central Asia: Postprint

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Abstract

To reveal the spatiotemporal distribution characteristics of stable isotopes in atmospheric precipitation in the alpine regions of Central Asia and to investigate hydrological cycles in arid regions at various scales, we analyzed hydrogen and oxygen stable isotope data in precipitation from 18 stations across the Tianshan, Kunlun, and Qilian Mountains in central Asia. The results demonstrate that seasonal variations in precipitation stable isotopes in the Tianshan, Kunlun, and Qilian Mountain regions are pronounced, exhibiting higher values during the summer half-year and lower values during the winter half-year. The spatial distribution of precipitation stable isotopes across the three regions also shows significant seasonal differences. With the exception of the Kunlun Mountains, the slopes of the local meteoric water line equations for both the Tianshan and Qilian Mountains are lower than that of the Global Meteoric Water Line, indicating that precipitation in these regions is strongly influenced by evaporation. Precipitation stable isotopes at all stations in the study area exhibit significant temperature effects, while precipitation amount effects are not apparent within the region. During spring and summer, the altitude effect on precipitation $ $18O is evident at three stations in the Kunlun Mountains region, with precipitation $ $18O decreasing with increasing elevation; no significant altitude effect is observed in other regions. Except for Xihexin in the Kunlun Mountains region, deuterium excess (d-value) across the Asian alpine regions generally exhibits a pattern of higher values in the winter half-year and lower values in the summer half-year.

Full Text

Preamble

Precipitation serves as a critical input factor in the water cycle and represents a primary source of surface water and groundwater, particularly in the arid regions of Central Asia. As an effective tracer, the isotopic composition of precipitation has become an important tool for investigating regional water cycle dynamics. To elucidate the spatial and temporal distribution of stable isotopes in precipitation across the arid areas of Central Asia, this study analyzed precipitation isotopic composition samples collected from 18 stations located in the Tianshan Mountains (including Wuqia, Akqi, Shali Guilank, Shenmuyuan, Bayanbulak, Balguntay, Huangshuigou, Urumqi River Hero Bridge, Barkol, and Yiwu), Kunlun Mountains (including Sharman, Xihexiu, and Jiangka), and Qilian Mountains (including Yeniugou, Dayekou, Daiqian, Jinqianyi, and Anyuan).

The isotopic composition was calculated using the following relationships. The δ notation is defined as:

$$\delta(‰) = \frac{R_b - R_j}{R_j} \times 1000$$

where R_b and R_j represent the isotopic ratios of the sample and V-SMOW standard, respectively. The $\delta^{18}O$ values were weighted by precipitation amount:

$$\delta^{18}O = \frac{\sum P_c \delta^{18}O_c}{\sum P_c}$$

where P_c and $\delta^{18}O_c$ denote the precipitation amount and $\delta^{18}O$ value for each sample.

2. Sampling Sites

The 18 sampling stations were distributed across three mountain ranges: the Tianshan, Kunlun, and Qilian Mountains. The Tianshan stations included: WT1 (Wuqia), WT2 (Akqi), WT3 (Shali Guilank), WT4 (Shenmuyuan), MT1 (Bayanbulak), MT2 (Balguntay), MT3 (Huangshuigou), MT4 (Urumqi River Hero Bridge), ET1 (Barkol), and ET2 (Yiwu). The Kunlun stations comprised WK1 (Sharman), WK2 (Xihexiu), and WK3 (Jiangka). The Qilian stations consisted of Q1 (Yeniugou), Q2 (Dayekou), Q3 (Daiqian), Q4 (Jinqianyi), and Q5 (Anyuan) [18-20].

Table 1. Information of the Sampling Sites in the Study Areas

Site	Altitude (m)	Longitude (°E)	Latitude (°N)	Sample Count	Temperature (°C)	Precipitation (mm)	$\delta^{18}O$ (‰)	δD (‰)	Sampling Period	Data Source
WT12176	75.25	39.72	8	7.7	188.7	-9.6	14.4	2012-08—2013-09	[18]
WT21985	78.45	40.93	10	6.8	237.7	-8.1	11.2	2012-08—2013-09	[18]
WT32005	78.54	40.94	61	16.70	331.4	-11.2	7.2	2012-05—2013-06	
WT41730	79.70	41.59	13	8.82	67.4	-13.5	5.2	2012-05—2013-06	
MT12458	84.15	43.03	13	-4.2	208.5	-14.8	14.3	2012-08—2013-09	[18]
MT21739	86.30	42.73	7	7.0	220.4	-9.6	10.3	2012-08—2013-09	[18]
MT32000	86.28	42.70	27	16.17	115	-6.0	6.1	2012-05—2013-06	
MT41880	87.20	43.37	82	5.75	-	-14.7	4.0	2012-05—2013-06	
ET1 1677	93.05	43.60	11	2.7	230.5	-15.4	9.4	2012-08—2013-09	[18]
ET2 1729	94.70	43.27	9	4.2	104.4	-13.8	10.7	2012-08—2013-09	[18]

Site	Altitude (m)	Longitude (°E)	Latitude (°N)	Sample Count	Temperature (°C)	Precipitation (mm)	$\delta^{18}O$ (‰)	δD (‰)	Sampling Period	Data Source
WK1	2004	38.94	75.70	22	11.4	51.6	-12.1	8.2	2012-07—2013-02	
WK2	2960	36.98	76.68	33	30.7	49.2	-13.3	14.4	2012-06—2013-10	
WK3	1507	37.73	77.25	57	11.8	59.5	-11.1	12.6	2011-07—2013-07	
Q1	3320	99.63	38.70	12	-3.1	405.8	-13.3	19.0	2008-06—2009-06	[19]
Q2	2720	100.28	38.57	47	0.7	-	-12.5	14.4	2012-11—2013-12	[19]
Q3	3300	102.57	37.22	112	-0.7	642.3	-8.2	16.1	2013-07—2014-06	[20]
Q4	2800	102.57	37.13	79	4.3	354.1	-7.4	11.0	2013-07—2014-06	[20]
Q5	2700	102.85	37.25	115	4.9	535.6	-8.6	17.8	2013-07—2014-06	[20]

Note: $\delta^{18}O$ and δD values represent weighted averages; "-" indicates missing data.

3. Results and Analysis

3.1 Seasonal Variation of $\delta^{18}O$

The seasonal variation of precipitation $\delta^{18}O$ in the alpine zones of Central Asia is illustrated in Figure 2. In the Tianshan region, the $\delta^{18}O$ values ranged from

-13.4‰ to -1.3‰, with corresponding δD values varying between -32.9‰ and -3.9‰. The isotopic composition exhibited pronounced seasonal fluctuations, with depleted values occurring during June-August and enriched values during August-December. The seasonal amplitude reached 8‰ to 12‰. In the Kunlun Mountains, $\delta^{18}O$ values varied from -35.4‰ to -7.4‰, with a seasonal amplitude of 5‰ to 12‰. The Qilian Mountains showed $\delta^{18}O$ values ranging from -25.7‰ to 4.3‰, with seasonal amplitudes of 8‰ to 11‰, and particularly depleted values during August-November.

The seasonal patterns revealed that precipitation isotopic composition was primarily controlled by temperature effects across all stations. At temperatures below 10°C, $\delta^{18}O$ values showed a strong positive correlation with temperature. However, when temperatures exceeded 10°C, this relationship weakened significantly, suggesting the influence of other factors such as moisture recycling and sub-cloud evaporation [12, 22, 29-30]. The d-excess values, calculated as $\delta D - 8\delta^{18}O$, exhibited seasonal variations opposite to those of $\delta^{18}O$, being higher in winter and lower in summer, consistent with findings from previous studies [15, 23].

3.6 Relationship Between $\delta^{18}O$ and Altitude

The relationship between precipitation $\delta^{18}O$ and altitude (h) was examined for the Tianshan, Kunlun, and Qilian Mountains. In the Tianshan region, a significant negative correlation was observed: $\delta^{18}O = -0.00118h - 9.19671$ ($R^2 = 0.59$). This altitude effect was particularly pronounced in the Kunlun Mountains during spring and summer, where $\delta^{18}O$ values decreased systematically with increasing elevation. In contrast, the altitude effect was weak in other regions and seasons. The spatial distribution of $\delta^{18}O$ values revealed that the isotopic lapse rate varied regionally, reflecting differences in moisture sources and atmospheric circulation patterns.

3.7 Spatial Distribution Characteristics

Following the methodology of Rozanski et al. [28], the spatial distribution of precipitation isotopes was analyzed. The d-excess values ranged from -14.7‰ to 21.7‰ across the study area, with a mean value of -7.2‰. The seasonal variation of d-excess showed a consistent pattern across the three mountain ranges, with higher values in winter and lower values in summer. The spatial distribution of $\delta^{18}O$ values revealed distinct regional patterns, with the most depleted values observed at high-altitude stations in the Kunlun Mountains and the most enriched values at lower-elevation stations in the Qilian Mountains. The isotopic composition of precipitation in the alpine zones of Central Asia was holistically depleted in winter and enriched in summer, except at the Xihexiu station in the Kunlun Mountains where an opposite pattern was observed.

Abstract

As an input factor of the water cycle, precipitation constitutes a primary source of surface water and groundwater, especially in arid Central Asia. As a useful tracer, the isotopic composition of precipitation has become an important tool for researching the regional water cycle. To reveal the spatial and temporal distribution of precipitation stable isotopes in the arid areas of Central Asia, this paper analyzed precipitation isotopic composition samples collected from 18 stations in the Tianshan Mountains (Wuqia, Akqi, Shali Guilank, Shenmuyuan, Bayanbulak, Balguntay, Huangshuigou, Urumqi River Hero Bridge, Barkol, and Yiwu), Kunlun Mountains (Sharman, Xihexiu, and Jiangka), and Qilian Mountains (Yeniugou, Dayekou, Daiqian, Jinqianyi, and Anyuan) in Central Asia.

According to the results, a clearly seasonal variation of the values of precipitation isotopic composition could be observed, and the values were high in summer but low in winter in these three regions. The seasonal fluctuation of the values in the three study regions was significant. The slopes of the atmospheric precipitation equation of the Tianshan Mountains and Qilian Mountains were lower than that of the global one except that of the Kunlun Mountains, which revealed that the regional precipitation in these regions was affected by the strong evaporation. Precipitation at all the stations was mainly affected by temperature. The values of precipitation $\delta^{18}O$ at the three stations in the Kunlun Mountains in spring and summer was obviously affected by altitude, and they were decreased with the increase of altitude but affected slightly in other regions. The d-values of the alpine zones in Central Asia were holistically high in winter but low in summer except at Xihexiu Station in the Kunlun Mountains.

Keywords: alpine zone; precipitation; stable isotope; spatiotemporal distribution; Central Asia

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