Advances in Research on Hydrogen and Oxygen Isotopes in Precipitation in Northwestern Arid Regions: Postprint

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Abstract

Based on recent relevant research literature, this study systematically reviews and summarizes the characteristics of hydrogen and oxygen isotopes in precipitation and related scientific issues in the arid region of Northwest China. The main findings are as follows: The stable isotopes in precipitation in the arid region of Northwest China exhibit significant seasonal variations, being higher in the summer half-year and lower in the winter half-year, which fully demonstrates the temperature effect on isotope distribution; spatially, the low isotope value areas are distributed in mountainous regions such as the Tianshan Mountains, while basins are high-value areas. Temperature is the primary controlling factor for the isotopic composition of atmospheric precipitation in the arid region of Northwest China; at the event precipitation scale, some regions exhibit a precipitation amount effect in summer; geographical factors and water vapor sources, among others, contribute to regional differences in the distribution of isotopes in atmospheric precipitation. Both the slope and intercept of the regional meteoric water line in the arid region of Northwest China are relatively low, indicating overall arid climatic characteristics, though significant internal regional differences exist. The deuterium excess values in precipitation show large variations, reflecting the complex water vapor sources in the arid region of Northwest China and significant differences in environmental elements during precipitation formation; deuterium excess generally exhibits higher values in winter and lower values in summer, but due to intense evaporation in summer, some stations also show the opposite pattern of lower values in winter and higher values in summer. The primary water vapor source for precipitation in the arid region of Northwest China is the westerlies, though it is also influenced by monsoons and polar air masses.

Full Text

Preamble

Hydrogen and Oxygen Isotopes in Precipitation in the Arid Regions of Northwestern China: A Review

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Abstract

Based on a comprehensive review of recent literature, this paper synthesizes research progress on hydrogen and oxygen isotopic characteristics in precipitation across the arid regions of northwestern China (ARNC). The main findings are as follows: (1) Precipitation stable isotopes in ARNC exhibit pronounced seasonal variation, with higher values in summer and lower values in winter, fully demonstrating the temperature effect on isotopic distribution. Spatially, isotopic minima occur in mountainous areas such as the Tianshan Mountains, while maxima appear in basins. (2) Temperature is the primary control on precipitation isotopic composition in ARNC. While some regions show a precipitation amount effect at the event scale during summer, geographical factors and moisture sources create regional differences in isotopic distribution. (3) Both the slope and intercept of the Local Meteoric Water Line (LMWL) in ARNC are relatively low, reflecting the region' s arid climate characteristics, though significant internal regional differences exist. (4) The d-excess values in precipitation show large variation ranges, indicating complex moisture sources and substantial differences in environmental conditions during precipitation formation. D-excess typically displays higher values in winter and lower values in summer, though some stations show the opposite pattern due to intense summer evaporation. (5) The dominant moisture source for precipitation in ARNC is the westerly belt, with additional influences from monsoon systems and polar air masses.

Keywords: atmospheric precipitation; hydrogen and oxygen isotopes; spatiotemporal distribution; moisture sources; arid regions of northwestern China

Introduction

Environmental isotopes widely present in natural water bodies exhibit distinct characteristics under different conditions of evaporation, condensation, precipitation, infiltration, and runoff [1]. As a critical component of the water cycle, variations in hydrogen and oxygen isotopes in precipitation provide valuable information for understanding hydrological processes and offer theoretical foundations for tracing moisture sources, reconstructing paleoclimates, and estimating evaporation fluxes [2]. The application of stable hydrogen and oxygen isotopes to water research began in the 1950s [3]. In 1961, the International Atomic Energy Agency (IAEA) and the World Meteorological Organization (WMO) established the Global Network of Isotopes in Precipitation (GNIP), initiating long-term global research on precipitation isotopes. With advances in isotope theory and analytical techniques, hydrogen and oxygen isotopes in precipitation have become effective tracers for studying complex hydrological cycles [4-5]. Scientists have conducted extensive research on global precipitation and related hydrological processes using stable isotope information, yielding numerous important results [6-12].

The arid regions of northwestern China, located in the heart of the Eurasian continent, encompass all of Xinjiang, the Hexi Corridor in Gansu, the Alxa Plateau in Inner Mongolia, and parts of Qinghai and Ningxia. These regions are generally defined as areas west of Helan Mountain with mean annual precipitation below 200 mm [Figure 1: see original paper] [13-14]. Characterized by alternating mountain ranges and basins/plains, the area features complex topography. Prevailing northwesterly winds in winter transport moisture primarily from Atlantic and Arctic sources via westerly airflow, while summer moisture from the Asian monsoon circulation system also exerts some influence [9, 15]. Notably, moisture from the adjacent Tibetan Plateau, particularly from glacial, snow, and precipitation evaporation in mountainous areas, represents another important regional moisture source [15]. These unique topographic and climatic conditions make it one of the world' s most arid regions. Numerous studies on precipitation isotopes have been conducted in ARNC, most based on site-specific data. However, due to scattered station distribution and fragmented research periods, these studies lack a comprehensive understanding of the region' s complex terrain, regional atmospheric circulation, and re-evaporation processes. Therefore, a systematic review and synthesis of research progress on precipitation hydrogen and oxygen isotopes across ARNC is urgently needed. This paper systematically reviews relevant studies on precipitation stable isotopes in ARNC, summarizes research areas and stations, and discusses research advances to provide insights for related hydrological process studies.

1. Research Areas and Stations

Precipitation isotope research in ARNC has primarily focused on the Tianshan Mountains and the Hexi Corridor. Studies in the Tianshan region began in the early 1980s or even earlier [16-17], concentrating mainly on the Urumqi River basin [18] with more recent work expanding to other watersheds [19-20]. Hexi Corridor research has centered on the Heihe [21-22], Shule [23-26], and Shiyang river basins [27]. In contrast, research on precipitation isotopes in the Alxa

Plateau, Qinghai, and Ningxia regions remains relatively limited [28].

Using GNIP data, scholars have studied precipitation isotopes at Urumqi [29], Hotan [30], and Zhangye [31] stations in ARNC [Figure 1: see original paper]. However, except for Hong Kong, all Chinese GNIP stations, including those in ARNC, suspended observations in the 2000s [32], rendering the data outdated and insufficient in station number for current research needs. Similar to GNIP, the Chinese Network of Isotopes in Precipitation (CHNIP) was established in 2004 based on the Chinese Ecosystem Research Network (CERN) field stations [33]. Using CHNIP data, Liu et al. [34] systematically analyzed the δ^{18}O distribution pattern in ARNC. With advances in observation and measurement technologies, many researchers have collected event-scale precipitation samples across ARNC through national meteorological monitoring networks, hydrological monitoring networks, CAS field stations, and even community-based approaches (e.g., local resident assistance), generating substantial detailed and reliable precipitation isotope datasets [35-51] [Figure 1: see original paper].

2. Sample Collection and Testing Methods

GNIP stations collect precipitation samples according to IAEA/WMO standards using standard rain gauges [29,52-53]. CHNIP stations employ polyethylene bottles with funnels as rain collectors, with ping-pong balls placed in funnels to prevent evaporation. Snow samples are collected in buckets after each snowfall event and melted indoors at room temperature. Monthly composite samples are transferred to 50 mL polyethylene bottles, thoroughly mixed, and analyzed at the Environmental Isotope Laboratory of the Institute of Geographic Sciences and Natural Resources Research, CAS, using a Finnigan MAT253 mass spectrometer with TC/EA method for δD and δ^{18}O determination, achieving measurement precisions of \$±\$1‰ and \$±\$0.3‰, respectively [54].

Studies based on national meteorological monitoring networks generally use similar collection methods: homemade rain collectors gather precipitation samples, which are sealed in sampling bottles after each event and stored at low temperatures to prevent evaporation before laboratory analysis. Variations exist among studies in collector design, bottle materials and sizes, storage conditions, and analytical instruments . Since sample collection is manual, differences in timing and methods inevitably affect isotopic precision, and varying measurement conditions influence results across study areas, potentially creating systematic differences. Therefore, standardizing collection and measurement procedures is essential for obtaining comparable data.

3.1 Spatiotemporal Distribution of Hydrogen and Oxygen Isotopes in Precipitation

As previously noted, the complex topography and moisture sources in ARNC determine the intricate spatiotemporal distribution of precipitation isotopes. Isotopic compositions across ARNC are summarized in . The data reveal large variation ranges, with δ^{18}O values spanning -33.4‰ to 8.5‰ and δD values from -263.2‰ to 59‰, both exceeding China’ s typical ranges (δD: -190‰ to 0‰; δ^{18}O: -24‰ to 2‰) [8]. This may reflect the limited representativeness of having only one sampling station (Urumqi) in ARNC in 1983.

Temporal characteristics show that precipitation isotopes are enriched during summer half-year and depleted during winter half-year. Based on CHNIP data, Liu et al. [34] found that precipitation isotopes in northwestern China generally enrich from January to July and deplete from August to December, with maxima in summer and minima in winter. Huang et al. [67] analyzed GNIP data from Urumqi and Zhangye, revealing consistent monthly δ^{18}O trends with notable increases from January to May (amplitude >10‰), frequent fluctuations from May to September, and overall higher values in summer and lower values in winter. Wang et al. [68] simulated precipitation isotopes in Central Asian arid regions using several GCM models, all successfully reproducing the seasonal pattern of higher summer and lower winter δ^{18}O values. Li et al. [69] observed similar seasonal enrichment-depletion patterns in the central Hexi Corridor, while Rao et al. [51] found that daily-scale precipitation δD and δ^{18}O values in the Alxa Plateau also vary seasonally, with higher values in summer and lower values in winter—a pattern that becomes more pronounced at monthly scales and resembles that of surrounding regions.

Spatial distribution is characterized by lower isotopic values in mountainous areas such as the Tianshan and Altai Mountains, and higher values in basins and the Hexi Corridor. Liu et al. [70] established a precipitation δ^{18}O pattern for China based on data from 55 regions, identifying mountainous areas as isotopic minima and basins as maxima in ARNC, consistent with measured distributions . Regional internal differences also exist: Liu et al. [71] found that Xinjiang’ s δ^{18}O decreases from Hotan to Urumqi during both summer and winter monsoon periods. Zhang et al. [72] reported higher isotopic values on the southern slopes than northern slopes of the Tianshan Mountains, attributing this to stronger evaporation on drier southern slopes that enriches precipitation isotopes. Wang et al. [58] observed similar patterns. In the Hexi Corridor, isotopes enrich eastward during winter, while complex moisture sources create more complicated spatial patterns in summer [67].

3.2 Factors Influencing Hydrogen and Oxygen Isotopes in Precipitation

Dansgaard [2] first identified factors controlling precipitation stable isotope spatiotemporal distribution, including temperature, latitude, altitude, precipitation amount, and continental effects—frameworks still widely used today. China’ s vast territory features complex geography and diverse climate conditions, with regionally distinct controlling factors [73].

Temperature effect dominates isotopic variation in ARNC . Numerous studies demonstrate temperature effects across different stations. Urumqi (500 m a.s.l.) and Daxigou (4200 m a.s.l.) in the same watershed show different δ^{18}O-temperature gradients, reflecting both altitude (temperature) differences and local convective precipitation influences. Liu et al. [45] found that Tianshan δ^{18}O values are more positive in summer and more negative in winter, with ~15‰ variation amplitude clearly controlled by temperature. Wang et al. [74] observed positive correlations between precipitation isotopes and temperature at event scales across Xinjiang' s Tianshan region. Zhou et al. [75] documented significant seasonal δ^{18}O variation at Linze station in the Hexi Corridor, with clear temperature effects.

Precipitation amount effect is less evident. Precipitation in ARNC concentrates in warm seasons, with little winter precipitation. During low-precipitation winters, heavy isotopes remain at low levels, increasing with precipitation amount. Thus, at seasonal scales, ARNC shows no clear precipitation amount effect—or even a reverse effect—because the temperature effect is overwhelmingly dominant. However, at event scales, some areas like the Heihe basin [35] and eastern Qilian Mountains [40] exhibit decreasing heavy isotopes with increasing precipitation amount. Further inland, in the Shule River [76], Qaidam Basin [36], and Tianshan region [74], the event-scale precipitation amount effect weakens or disappears.

Geographical factors, including altitude, latitude, and longitude [63], significantly influence spatial distribution. Watershed-scale altitude effects are common [77]: on windward slopes, lower altitudes show enriched heavy isotopes that become increasingly depleted with elevation, typically showing negative gradients [78]. The Urumqi River [60], Heihe [35], and Shiyang River basins [79] all show increasing δ^{18}O from source to downstream. Ma et al. [80] found a mean altitude gradient of -0.26‰ $\cdot$ $(100\text{m})^{-1}$ in the Qilian Mountains, with steeper gradients in summer than winter. The Hexi region shows δ^{18}O and δD gradients of -0.23‰ $\cdot$ $(100\text{m})^{-1}$ and -1.67‰ $\cdot$ $(100\text{m})^{-1}$, respectively. However, some studies [81] reported a positive δ^{18}O-altitude gradient of 0.12‰ $\cdot$ $(100\text{m})^{-1}$ on the Tianshan lee side, attributed to local sub-cloud secondary evaporation and moisture recycling. Li et al. [41] compared north and south slopes of Wushaoling Mountain, finding steeper gradients on the south slope due to lower temperatures enhancing condensation and depleting heavy isotopes, while stronger sub-cloud evaporation on the north slope enriched isotopes. Gao [82] calculated a continental gradient of -2.9\$$\times 10^{\{-3\}‰ \cdot km}$\{-1\}\$ for northwestern China using June-September data.

Beyond local geographical factors, regional climatic background—including moisture source properties and vapor pressure—also determines precipitation isotopic composition [83]. Many studies have investigated these influences in ARNC. During summer, the eastern and central Hexi Corridor experiences southeast and southwest monsoon influences, showing precipitation amount effects and lower isotopic values than other ARNC areas [40,84]. In winter, dynamic fractionation dominates, with raindrops undergoing secondary evaporation and mixing with locally re-evaporated moisture, causing gradual δ^{18}O enrichment along westerly trajectories [34,53,85-86]. In large Tianshan oases like Urumqi, recycled moisture contributes ~16.2% of precipitation. Since re-evaporated moisture from surface evaporation and transpiration is isotopically depleted, substantial contributions can progressively deplete precipitation stable isotopes [87].

Vapor pressure also significantly and positively correlates with precipitation isotopes. Li et al. [44] found positive correlations between hydrogen isotopes and vapor pressure in the Tuolai River basin, though the relationship weakens from higher to lower elevations. Ren et al. [88] combined GNIP data with meteorological observations in eastern northwestern China, finding that when vapor pressure deficit exceeds 0.52 kPa, sub-cloud evaporation causes δ^{18}O to increase significantly with vapor pressure deficit. These positive correlations reflect the unique climatic environment of arid regions [69].

3.3 Local Meteoric Water Line (LMWL) Studies

Craig [89] established the Global Meteoric Water Line (GMWL) as $\delta D = 8\delta^{18}O + 10$, later refined by Rozanski et al. [90] to $\delta D = 8.17\delta^{18}O + 10.35$. Zheng et al. [8] derived China’ s meteoric water line as $\delta D = 7.9\delta^{18}O + 8.2$ based on 1980 data from eight stations, showing little difference from the GMWL.

At regional scales, LMWL slopes and intercepts often differ substantially from the GMWL due to varying geography and climate. While the GMWL serves as a baseline [91], its simplicity limits practical application, prompting development of local-scale meteoric water lines [92]. Many scholars have fitted LMWLs for ARNC regions and stations. Huang et al. [93] derived $\delta D = 7.56\delta^{18}O + 5.05$ ($R^2 = 0.97$) for northwestern China using GNIP data, while Cheng et al. [94] proposed $\delta D = 7.55\delta^{18}O + 6.61$ ($R^2 = 0.98$) for westerly-dominated regions (including most of ARNC), showing remarkably similar results.

Precipitation evaporation drives deviations from the meteoric water line along evaporation lines with slopes <8 [95]. Arid regions with low precipitation and high evaporation thus exhibit slopes and intercepts lower than global values, with higher temperatures, stronger evaporation, and lower humidity further reducing these parameters [96]. LMWLs for selected ARNC stations are presented in . Overall, most stations show lower slopes and intercepts than global and national lines, reflecting ARNC’ s arid climate and strong evaporative imbalance [82]. Qilian station’ s slope of 8.3 exceeds the GMWL slope, primarily because high altitude and low precipitation temperatures (mostly solid precipitation) cause non-equilibrium fractionation that preferentially enriches deuterium over δ^{18}O, increasing d-excess and consequently slope and intercept values [23]. The Shule River basin’ s low intercept reflects moisture cycling patterns [43], while the Tuolai River basin’ s lower slope and intercept compared to neighboring basins suggest influence from dry atmospheric conditions and evaporation [44]. Xinjiang shows the lowest slopes and intercepts in ARNC, indicating intense evaporation. Within Xinjiang, the relatively more humid and cooler northern Tianshan shows higher slopes and intercepts than the southern Tianshan due to sub-cloud evaporation [58,97]. Li et al. [98] found lower LMWL slopes in oasis areas than mountainous areas of the Hexi region, indicating stronger secondary evaporation effects on precipitation in oases.

3.4 d-excess and Moisture Source Studies

d-excess is defined as d = δD - 8δ^{18}O [2], with typical inland values near 10‰ [89]. Studies indicate that d-excess inversely correlates with relative humidity at the moisture source [101]. Because d-excess preserves source information and remains unchanged during transport, it serves as an effective tracer for moisture sources [102-104], complementing back-trajectory methods for ARNC moisture source identification. In arid regions, d-excess decreases during evaporation but increases during local moisture recycling from intense evaporation [105].

Xinjiang' s d-excess characteristics are complex. Some stations show higher values in cold seasons and lower values in warm seasons [46,59,106], with Wang et al. [46] attributing summer low d-excess to westerly air masses and intense evaporation enriching heavy isotopes. Conversely, other stations exhibit opposite patterns [30,53,107], possibly related to strong local moisture recycling in summer. The Jiangka station on the southern Tarim Basin margin shows winter-low, summer-high d-excess, likely due to re-evaporation of summer precipitation and ascent of isotopically light evaporated moisture to mountainous areas, increasing d-excess at high altitudes [50].

Many studies have used d-excess to investigate Xinjiang' s moisture sources. Wang et al. [46] combined δ^{18}O, d-excess, and NCEP/NCAR reanalysis data, finding that Yushugou River basin spring precipitation originates mainly from Europe and western Russia, occasionally influenced by polar moisture, while summer precipitation derives from westerly air masses and local recycled moisture. Xie [108] quantitatively calculated that Xinjiang's largest moisture contributors are local Xinjiang sources and Central Asia, with source regions shifting northward in summer and southward in winter. Mu [109] found that local evaporated moisture significantly supplies low-level water vapor in southern Xinjiang, with moisture recycling involving evaporation from lower elevations ascending to mountains. Sun et al. [61] analyzed stable isotopes in high-mountain precipitation across central Asia, finding large d-excess fluctuations indicating complex precipitation processes and moisture sources. Moisture sources also affect d-excess magnitude: moisture from the northern Atlantic (including Urumqi) produces low summer d-excess due to high oceanic relative humidity, but high winter d-excess from low humidity conditions. In contrast, Altai Mountains show weak seasonal d-excess variation, likely due to different transport mechanisms involving both Atlantic and Arctic moisture sources [110].

Overall, the Hexi Corridor also shows winter-high, summer-low d-excess [41,76,84,100], attributed to stronger westerlies in summer bringing humid Atlantic air and monsoon influence, reducing d-excess, while winter moisture from westerlies and drier polar air masses increases d-excess [39,101,111].

Some areas show unique local characteristics: Qingtu Lake at the Shiyang River’ s lower end exhibits large d-excess fluctuations without clear seasonality due to combined influences of continental air masses, monsoons, seasonal evaporation differences, and artificial lake evaporation [112]. Li et al. [64] found that in Shiyang River mountainous areas, weaker sub-cloud evaporation at low temperatures causes d-excess to increase with altitude. Zhao et al. [22] determined that d-excess in the upper Heihe River relates to moisture sources and local relative humidity, with seasonal precipitation patterns and sub-cloud evaporation also influencing values.

Numerous studies have investigated Hexi Corridor moisture sources. Guo et al. [37] found Dunhuang Basin d-excess variations similar to Urumqi, indicating year-round westerly control, with winter-spring influences from Siberian-Mongolian polar air masses and summer contributions from southwest monsoons and local recycled moisture. Zhang et al. [113] documented large d-excess fluctuations in Heihe River precipitation events, confirming complex moisture sources and evaporation conditions. Wu et al. [35] used back-trajectory methods with stable isotopes and d-excess to identify cold-season moisture primarily from westerlies and warm-season moisture from complex sources including substantial inland moisture recycling. Zhao [76] traced Shule River moisture to westerly sources from Central Asia or high-latitude Europe, isotopically low westerly moisture from the Atlantic, local recycled moisture from regional evaporation, summer southwest monsoons from the Indian Ocean, and winter moisture potentially from the Tibetan Plateau. Ma et al. [114] integrated δ^{17}O and d-excess data to show that eastern Qilian Mountains precipitation is controlled by local water cycling and continental air masses, influenced by westerlies and southeast monsoons (mainly in summer). Li et al. [115] identified typical monsoon precipitation events in the Hulugou basin of central Qilian Mountains, confirming that although infrequent and short-duration, monsoon events contribute to local precipitation.

In summary, Xinjiang’ s primary moisture sources are westerly air masses and local recycled moisture, shifting northward in summer and southward in winter. The Hexi Corridor is also dominated by westerlies year-round, with winter polar air mass influences and summer contributions from southeast monsoons, local recycled moisture, and southwest monsoons. While many studies [56,116-117] have reached similar conclusions for Xinjiang and the Hexi Corridor, research on moisture sources in the Qaidam Basin and Alxa Plateau remains notably scarce.

4. Conclusions and Recommendations

In conclusion, hydrogen and oxygen isotopes in precipitation are effective tools for studying water cycle mechanisms. The establishment of isotope observation networks from GNIP to CHNIP has greatly advanced understanding of isotopic spatiotemporal distribution in ARNC. Recent technological progress has enabled new precipitation isotope stations and increasingly fine-scale isoscape research, improving regional understanding. However, several issues require further investigation:

1. (1) The complex geography and harsh climate of ARNC make precipitation sampling difficult. Current research remains spatially concentrated in Xinjiang and the Hexi Corridor, with limited studies in the Qaidam Basin and Alxa Plateau.
2. (2) Sample collection and measurement procedures vary among studies, requiring standardization to improve data accuracy and comparability.
3. (3) The relationship between precipitation and water vapor isotopic composition needs further investigation.
4. (4) While recent technological advances have enabled widespread δ^{17}O application, δ^{17}O research remains limited in ARNC.

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