Precipitation Geochemistry and Controlling Factors at the Koxkar Glacier Terminus, Tianshan Mountains: Postprint

Authors: Wang Jian, Han Haidong

Date: 2022-03-28T12:10:10+00:00

Abstract

Summer precipitation was sampled at the terminus of Koxkar Glacier on the southern slope of the Tianshan Mountains in an inland alpine region. Based on the analysis of ion concentrations, conductivity, and pH values, factor analysis, enrichment factors, and backward trajectory methods were employed to investigate the solute sources and controlling factors of regional precipitation. The results indicate that: (1) The pH values of atmospheric precipitation at the terminus of Koxkar Glacier ranged from 7.15 to 8.52, being weakly alkaline overall. The anions and cations were dominated by HCO-3 and Ca2+, respectively, belonging to the typical HCO3-Ca type. The conductivity and total ion concentration of daytime precipitation were 11.56% and 9.40% higher than those at night, respectively. This may be attributed to wet deposition after aerosol materials from the Tarim Basin migrated to the study area with near-surface winds from the foothill zones and plain areas under the action of valley winds or glacier winds. (2) Precipitation ions were primarily supplied by crustal source materials, accounting for 85.54% of the total ion content. Among them, HCO-3, Ca2+, and Mg2+ were mainly supplied by the weathering of carbonate rocks (CaxMg1-xCO3) in Jurassic sedimentary layers and Quaternary loess deposits, while Cl-, SO2-4, Na+, and K+ were primarily supplied by the weathering of salt soils formed through the evaporation of salt lakes (brackish lakes) developed due to aridity in Central Asia and the Tarim Basin or by alluvial/pluvial processes. Only 41.52% of Na+ and 96.22% of Cl- in precipitation originated from marine sources, with a concentration ratio of 2.13:1 between them. This indicates that marine-source air masses were significantly affected by factors such as precipitation re-evaporation and surface material wind erosion during long-distance transport, resulting in marine-source contributions accounting for only 4.87% of total precipitation ions. Solutes supplied by anthropogenic sources were approximately twice those from marine sources, dominated by NH+4, NO-3 and

$SO2\text{-}4$, which can provide necessary nitrogen and sulfur elements for soil formation and vegetation growth in alpine regions. (3) Backward trajectory tracking of air masses indicated that westerly circulation exerted a very significant influence on precipitation and its chemical composition on the southern slope of the Tianshan Mountains. On average, the frequency and amount of precipitation generated accounted for 64.35% and 53.04%, respectively. Although the total ion concentration in its precipitation was only 69.91% of that from local circulation, the NO-3 concentration was 1.42 times that of precipitation from local circulation on average, indirectly suggesting that air and water quality in the Tarim Basin may be affected by human activities in Central Asia.

Full Text

Chemical Characteristics and Controlling Factors of Precipitation at the Terminus of the Koxkar Glacier, Tianshan Mountains

WANG Jian[1], HAN Haidong[2], XU Junli[1], YAN Wei[3]

[1]North Jiangsu Research Institute of Agricultural and Rural Modernization, Yancheng Teachers University, Yancheng, Jiangsu 224007, China
[2]State Key Laboratory of Cryospheric Science, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou, Gansu 730000, China
[3]School of Geographic Sciences, Xinyang Normal University, Xinyang, Henan 464000, China

Abstract

Atmospheric precipitation samples were collected during summer at the terminus of the Koxkar Glacier on the southern slopes of the Tianshan Mountains. Based on analyses of ion concentrations, electrical conductivity, and pH characteristics, we investigated the solute sources and controlling factors of regional precipitation using factor analysis, enrichment factors, and backward trajectory tracking. The results indicate that: (1) Atmospheric precipitation at the glacier terminus had a pH ranging from 7.15 to 8.52, indicating weak alkalinity. Anions and cations were dominated by HCO_3^- and Ca^{2+}, respectively, classifying it as a typical HCO_3^--Ca^{2+} type. The electrical conductivity and total ion concentration of daytime precipitation were 7.15–8.52% and 11.56% higher than those of nighttime precipitation, respectively, likely due to wet deposition of aerosol materials from the piedmont and plain areas of the Tarim Basin transported by near-surface winds under the influence of valley or glacier winds. (2) Precipitation ions primarily originated from crustal source materials, accounting for 85.54% of total ion content. Specifically, HCO_3^-, Ca^{2+}, and Mg^{2+} were mainly supplied by weathering of carbonate rocks ($CaxMg_1\ CO_3$) in Jurassic sedimentary layers and Quaternary loess deposits, while Cl^-, Na^+, and K^+ were mainly supplied by evaporation from salt lakes (or brackish lakes) developed under arid conditions in Central Asia and the Tarim Basin, or by weathering of saline soils formed by alluvial-proluvial processes. Only 41.52% of Na^+ and 96.22% of Cl^- originated from oceanic sources, with a concentration ratio of 2.13:1, indicating that oceanic air masses were significantly affected by precipitation re-evaporation and surface material wind erosion during long-distance transport, resulting in oceanic sources contributing only 4.87% of total precipitation ions. (3) Solutes from human activities were approximately double those from oceanic sources, primarily consisting of NO_3^-, NH_4^+, and SO_4^{2-}, which can provide essential nitrogen and sulfur elements for soil formation and vegetation growth in alpine regions. (4) Backward trajectory tracking of air masses revealed that westerly circulation significantly influences precipitation and its chemical composition on the southern slopes of the Tianshan Mountains, accounting for 64.35% of precipitation events and 53.04% of precipitation amount on average. Although the total ion concentration in precipitation formed by westerly circulation was only 69.91% of that from local circulation, its average concentration was 1.42 times higher, indirectly indicating that air and water quality in the Tarim Basin may be affected by human activities in Central Asia.

Keywords: atmospheric precipitation; solute source; human activity; water vapor transport; alpine regions

1.1 Study Area Overview

The precipitation sampling site in this inland alpine region is located in a high-altitude natural pasture approximately 3 km from the terminus of the Koxkar Glacier on the southern slopes of Mt. Tomur in the Tianshan Mountains, about 45 km from Aksu City (41°42 N, 80°10 E, 2996 m a.s.l.). The site experiences a mean annual temperature of approximately 0.77°C and mean annual precipitation of about 600 mm, primarily occurring during the glacier ablation and vegetation growing season from May to September. The Tianshan glacial region serves as a reliable water source for the Tarim River, with a glacial area of 3200 km^2 in the Kumalike River source region alone. The extensive modern glaciers are key factors in the formation of glacier winds. Although the glacier ablation zone is covered with large amounts of loose debris, which can affect the hydrochemistry of outflow runoff, the debris—often moist or frozen due to precipitation and meltwater infiltration—has negligible influence on precipitation chemistry compared to loose materials in piedmont and plain areas. The Tarim Basin to the south features extensive Gobi and desert landscapes, with the Taklamakan Desert providing abundant soluble materials for precipitation under conditions of mean annual precipitation <100 mm, mean annual wind speed of 1.7-1.8 $m \cdot s^{-1}$, and evaporation exceeding 1100 mm. Additionally, under westerly circulation, loose materials and evaporite from brackish lakes (e.g., Issyk-Kul) in Central Asia may serve as important sources of aeolian deposits and aerosols for the Tarim region.

1.2 Data Collection and Analysis

Precipitation sampling was conducted systematically from May to September (the glacier ablation and alpine pasture vegetation growing season) at a meteorological observation field near the Koxkar Glacier terminus. At the onset of precipitation, a porcelain-enamel basin (diameter 0.8 m) cleaned with deionized water was placed on a stand. After precipitation ceased, the basin was immediately rinsed three times with the collected precipitation, then the sample was transferred to a polyethylene bottle that had been washed with deionized water. For solid precipitation (snow, sleet, or hail), samples were first collected in sealed bags, compacted to remove air, and allowed to melt at room temperature before the same procedure was followed. Samples were then stored sealed, at low temperature, and protected from light. A total of 134 precipitation events were collected, with precipitation amounts ranging from 0.2 to 21.6 mm and a total precipitation of 690.4 mm, representing 76.05% of the sampling period total.

In the laboratory, a PHSJ-3F conductivity meter measured electrical conductivity (EC), a DDS-307A pH meter measured pH, and a Dionex-300 ion chromatograph measured anions (Cl^-, ${NO_3}^-$, ${SO_4}^{2-}$) while a Dionex-600 measured cations (Na^+, K^+, Mg^{2+}, Ca^{2+}, ${NH_4}^+$). Concentrations were measured in $mg \cdot L^{-1}$ with errors <5%. For data reliability verification and ion relationship analysis, concentrations were converted from $mg \cdot L^{-1}$ to $eq \cdot L^{-1}$ using: C = C × 10^3 × e / M , where C is the equivalent concentration ($eq \cdot L^{-1}$), C is mass concentration ($mg \cdot L^{-1}$), e is ionic charge, and M is molar mass ($g \cdot mol^{-1}$). Weighted averages for EC and ion concentrations were calculated as: A = Σ(a × P) / ΣP , where A is the weighted average concentration ($eq \cdot L^{-1}$ or $S \cdot cm^{-1}$), a is the concentration of ion i in event j, P is precipitation amount (mm), and n is the number of events.

1.3 Quality Control

Charge balance principles were applied for quality control. Typically, the charge balance between anions and cations in water bodies ranges from 0.9 to 1.1. Given the limited number of measured ions in precipitation samples, the charge balance ratio was calculated as Σcations/Σanions = 1:6.34, indicating missing anion species. The correlation coefficient between calculated and measured Ca^{2+} concentrations was 0.859 (Sig.<0.01), confirming overall data reliability. Samples were screened to exclude: (1) events with precipitation <2 mm; (2) events where evaporation exceeded precipitation; and (3) data points beyond c ± 2S , where c is the mean and S is the standard deviation of each parameter. After removal, 134 samples remained for analysis.

1.4 Enrichment Factor Analysis

Enrichment factor (EF) analysis quantifies precipitation chemical sources. Following Keene et al. and Xiao et al., Na^+ was selected as the marine source indicator because its marine source EF values were >10, indicating significant enrichment relative to seawater and confirming its suitability as a reference element. Marine reference concentrations came from the Global Precipitation Chemistry Project and Atlantic measurements, while crustal reference abundances came from Li Tong' s data on the Tarim-North China plate crust and lithosphere. EF interpretation follows: EF 1 indicates similar sources to the reference; 1<EF$ $10 indicates the reference is an important source; EF>10 indicates significant enrichment relative to the reference, making it a non-dominant source.

The EF equations are:

Relative to marine source:

$$EF_{\text{marine}} = \frac{[X_i]/[Cl^-]_{\text{precipitation}}}{[X_i]/[Cl^-]_{\text{ocean}}}$$

Relative to crustal source:

$$EF_{\text{crust}} = \frac{[C_i]/[Ca^{2+}]_{\text{precipitation}}}{[Y_i]/[Ca^{2+}]_{\text{crust}}}$$

where [X] and [Y] are concentrations of ion i in ocean and crust, respectively.

Source apportionment formulas are:

Marine source input:

$$MSF_i = \frac{[X_i]/[Cl^-]_{\text{ocean}}}{[X_i]/[Cl^-]_{\text{precipitation}}} \times 100\%$$

Crustal source input:

$$CF_i = \frac{[Y_i]/[Ca^{2+}]_{\text{crust}}}{[C_i]/[Ca^{2+}]_{\text{precipitation}}} \times 100\%$$

Human activity input:

$$AF_i = (1 - MSF_i - CF_i) \times 100\%$$

where MSF , CF , and AF represent the proportional inputs from marine, crustal, and human activity sources for ion i.

1.5 HYSPLIT Clustered Backward Trajectory Model

The HYSPLIT model from NOAA's Air Resources Laboratory (https://www.arl.noaa.gov/hysplit-2/) was used to track air mass origins. Starting heights of 100 m, 500 m, and 1000 m were selected based on the study area' s elevation (~3000 m) and the characteristic "small rains daily, large rains every three days" pattern. Cluster analysis used a 120-hour interval to identify distinct moisture source pathways.

2.1.1 Chemical Composition Characteristics

The 134 valid precipitation samples had pH values ranging from 7.15 to 8.52 (mean 7.85), indicating weak alkalinity. EC ranged from 3.51 to 60.75 $S \cdot cm^{-1}$ (mean 237.67 $S \cdot cm^{-1}$). Anions and cations were dominated by HCO_3^- (84.23% of anions) and Ca^{2+} (71.52% of cations), respectively, classifying the precipitation as HCO_3^--Ca^{2+} type. The concentration order was $HCO_3^- > SO_4^{2-} > NO_3^- > Cl^-$ for anions and $Ca^{2+} > NH_4^+ > Mg^{2+} > Na^+ > K^+$ for cations, though significant temporal variations existed.

Compared with Tianjin and Shangluo in central-eastern China—regions with denser vegetation and stronger human activities—the study area shows weaker industrial/agricultural activity but abundant terrestrial and marine sedimentary materials weathered into loose surface deposits rich in carbonate minerals. Consequently, pH values are higher and HCO_3^- proportions significantly larger, while SO_4^{2-} and NO_3^- proportions are notably smaller. Compared with arid northwestern regions like Alxa Right Banner, the study area shows significantly lower SO_4^{2-}/NO_3^- ratios due to stronger pastoral activities but distance from industrial zones. Relative to remote sites like the Dongkemadi Glacier and Waliguan Baseline Observatory on the Tibetan Plateau, total ion concentrations are substantially higher because sparse vegetation in northwestern arid regions provides abundant soluble materials to atmospheric aerosols from loose surface deposits. However, compared with Heisongyi in the eastern Qilian Mountains, the study area' s HCO_3^- and total ion concentrations are approximately half, attributable to higher precipitation (~600 mm vs. ~290 mm) causing greater dilution.

2.1.2 Temporal Variations in Precipitation Composition

The sampling site lies in a glacier trough oriented roughly east-west. Near-surface winds (at 2 m height) are predominantly westerly (76.32% frequency), supplemented by easterly and northeasterly winds. Valley or glacier winds may create local circulation patterns. At night (21:00–10:00), westerly winds increase in frequency and speed due to mountain and glacier wind effects, while daytime shows reduced westerly winds and enhanced easterly winds, potentially forming mountain-valley winds.

Daytime precipitation EC and total ion concentration were 11.56% and 9.40% higher than nighttime values, respectively. This likely occurs because during the day, aerosol materials from the Tarim Basin are transported to the study area by near-surface winds and deposited via precipitation. However, nighttime precipitation showed significantly higher concentrations of human activity indicators (NO_3^-, NH_4^+, SO_4^{2+}), with NO_3^- 25.58% higher and NH_4^+ 73.74% higher than daytime values. This suggests that westerly circulation transports pollutants from human activities in Central Asia, significantly contributing to precipitation solutes. The ratio of NO_3^- to NH_4^+ was 2.13:1, consistent with biomass burning or animal waste decomposition in the predominantly agricultural/pastoral Central Asian region.

Seasonally, as the continental high-pressure system weakened, westerly circulation intensified, increasing dust transport from Central Asia. Total ion concentration increased from 888.81 to 1305.89 $\mathrm{eq \cdot L^{-1}}$ (46.93% increase), and EC increased from 49.54 to 68.84 $\mathrm{S \cdot cm^{-1}}$ (38.96% increase). Poor correlations between temperature, total radiation, wind speed, and ion concentrations confirmed that evaporation did not significantly affect sample integrity. While precipitation amount generally controls ion concentrations through dilution, this relationship was not significant at monthly scales because solute concentrations and hydrochemical types are primarily governed by source strength and supply intensity.

2.2.1 Solute Sources in Precipitation

Factor analysis of solute parameters (Table 2) with varimax rotation yielded three principal components explaining 88.29% of total variance. Factor 1 (58.48% variance) loaded heavily on HCO_3^-, Ca^{2+}, and Mg^{2+}, with Ca^{2+}-Mg^{2+} correlation of 0.859 ($p<0.01$), indicating a common source: carbonate rock weathering ($CaxMg_1$ CO_3) from dust particles that undergo carbonation during atmospheric transport and wet deposition. This factor also loaded on EC, confirming carbonate weathering dominance. The widespread Jurassic coal-bearing clastic sediments in intermontane basins and adjacent Quaternary loess deposits in the Tarim Basin and Central Asia provide abundant carbonate-rich weathering materials.

Factor 2 (15.67% variance) loaded on Cl^-, Na^+, and K^+, with Cl^--Na^+ correlation of 0.859 ($p<0.01$). In the Eurasian interior far from modern oceans, these ions originate from salt lake evaporation, paleo-marine residue weathering, or saline soil from alluvial-proluvial processes. Factor 3 (14.14% variance) loaded on NO_3^- and NH_4^+, with a concentration ratio of 2.13:1, indicating complex sources including aerosol nitrogen nitrification and industrial pollution. NH_4^+ generally originates from agricultural activities and animal waste decomposition, existing as suspended particles in the atmosphere.

2.2.2 Contributions from Marine and Human Activity Sources

Enrichment factor analysis (Table 3) shows all ions except Na^+ have EF_{marine} > 10, indicating precipitation solutes are significantly enriched relative to seawater and dominated by non-marine sources, consistent with the inland continental location. For crustal sources, EF_{crust} values for Ca^{2+}, Mg^{2+}, and HCO_3^- are <1, indicating depletion relative to crustal abundance, while Na^+, Cl^-, K^+, SO_4^{2-}, NO_3^-, and NH_4^+ show EF_{crust} > 10, indicating significant enrichment relative to crustal sources.

Source apportionment (Table 4) reveals crustal input averages 85.54% of total ions (by equivalent concentration), with carbonate weathering contributions (Ca^{2+}, Mg^{2+}, HCO_3^-) matching the 58.48% variance explained by Factor 1. Evaporite weathering contributions (Cl^-, Na^+, K^+) account for 91.38%, consistent with Factor 2. Human activity input averages 9.71% of total ions, nearly double the marine input of 4.87%. Human activities, particularly livestock husbandry around the sampling site and throughout the Tianshan region, contribute significantly through biomass burning and animal waste decomposition, providing essential nutrients (NO_3^-, NH_4^+, SO_4^{2-}) for alpine vegetation.

2.3 Backward Trajectory Analysis of Water Vapor

HYSPLIT clustered backward trajectories identified four moisture source pathways (Table 5). Westerly circulation (Path 1) was most significant, accounting for 58.46% of precipitation events and 53.42% of precipitation amount. Local circulation (Path 2) accounted for 33.39% of events and 43.42% of precipitation. Paths 3 and 4 contributed minimally (2.26% and 3.54% of precipitation, respectively). Although precipitation from westerly circulation had lower total ion concentration (1017.81 $\text{eq} \cdot \text{L}^{-1}$) than local circulation (1497.83 $\text{eq} \cdot \text{L}^{-1}$), its average concentration was 1.42 times higher, indicating that air masses undergo significant modification during long-distance transport. Precipitation re-evaporation and surface weathering material entrainment reduce marine source contributions to only 9.95% of total ions, while human activity inputs from Central Asia contribute 4.87%. This suggests that air and water quality in the Tarim Basin may be affected by human activities in Central Asia.

3 Conclusions

1) Precipitation at the terminus of the Koxkar Glacier on the southern slopes of Mt. Tomur had pH values of 7.15–8.52 (mean 7.85), indicating weak alkalinity. With EC of 3.51-60.75 $\text{S} \cdot \text{cm}^{-1}$ (mean 237.67 $\text{S} \cdot \text{cm}^{-1}$), anions and cations were dominated by HCO_3^- and Ca^{2+}, respectively, classifying it as a typical HCO_3^--Ca^{2+} type. The concentration order was HCO_3^- > SO_4^{2-} > NO_3^- > Cl^- for anions and Ca^{2+} > NH_4^+ > Mg^{2+} > Na^+ > K^+ for cations.

2) Factor analysis revealed that weathering of carbonate rocks ($CaxMg_1$ CO_3) in Jurassic sedimentary layers and Quaternary loess deposits is the primary solute source, contributing 85.54% of total ions, mainly as HCO_3^-, Ca^{2+}, and Mg^{2+}. Evaporation from salt lakes in Central Asia and the Tarim Basin, and weathering of alluvial-proluvial saline soils, significantly influence precipitation chemistry, supplying Cl^-, Na^+, and K^+. Addi-

tionally, surrounding pastures and agricultural/pastoral activities around the Tianshan region are important sources of NO_3^-, NH_4^+, and SO_4^{2-}, providing essential nutrients for alpine vegetation growth.

3) Enrichment factor analysis showed that precipitation solutes are dominated by crustal sources (85.54% of total ions), with marine sources contributing only 4.87%. Human activity inputs averaged 9.71%, nearly double the marine contribution. Westerly circulation significantly affects precipitation chemistry in southern Xinjiang, accounting for 64.35% of events and 53.04% of precipitation amount. Although total ion concentration from westerly circulation was only 69.91% of local circulation, its average concentration was 1.42 times higher, suggesting that air and water quality in the Tarim Basin may be impacted by human activities in Central Asia.

References

[1] Laouali D, Delon C, Adon M, et al. Source contributions in precipitation chemistry and analysis of atmospheric nitrogen deposition in a Sahelian dry savanna site in West Africa[J]. Atmospheric Research, 2021, 251: 105423.

[2] Vet R, Artz R S, Carou S, et al. A global assessment of precipitation chemistry and deposition of sulfur, nitrogen, sea salt, base cations, organic acids, acidity and pH, and phosphorus[J]. Atmospheric Environment, 2014, 93: 3-100.

[3] Akpo A, Galy Lacaux C, Laouali D, et al. Precipitation chemistry and wet deposition in a remote wet savanna site in West Africa: Djougou (Benin)[J]. Atmospheric Environment, 2015, 115: 110-123.

[4] Wang S Y, He X B, Wu J K, et al. Chemical characteristics and ionic sources of precipitation in the source region of the Yangtze River[J]. Environmental Science, 2019, 40(10): 4431-4438.

[5] Galy Lacaux C, Laouali D, Descroix L, et al. Long term precipitation chemistry and wet deposition in a remote dry savanna site in Africa (Niger)[J]. Atmospheric Chemistry and Physics, 2009, 9: 1579-1595.

[6] Cook E M, Sponseller R, Grimm N B, et al. Mixed method approach to assess atmospheric nitrogen deposition in arid and semi-arid ecosystems[J]. Environmental Pollution, 2018, 239: 617-630.

[7] Xiao J, Jin Z D, Hu D, et al. Geochemistry and solute sources of surface waters of the Tarim River Basin in the extreme arid region, NW Tibetan Plateau[J]. Journal of Asian Earth Sciences, 2012, 54-55: 162-173.

[8] Chen X L, Song Y G, Li Y, et al. Provenance of subaerial surface sediments in the Tarim Basin, Western China[J]. Catena, 2021, 198: 105014.

[9] Wu G J, Zhang X L, Zhang C L, et al. Concentration and composition of dust particles in surface snow at Urumqi Glacier No.1, Eastern Tien Shan[J].

Global and Planetary Change, 2010, 74: 34-42.

[10] Wang J, Han H D, Zhao Q D, et al. Hydrochemical denudation and transient carbon dioxide drawdown in the highly glacierized, shrinking Koxkar basin, China[J]. Advances in Meteorology, 2016, 1: 1-11.

[11] Wu H W, Wu J L, Li J, et al. Spatial variations of hydrochemistry and stable isotopes in mountainous river water from the Central Asian headwaters of the Tajikistan Pamirs[J]. Catena, 2020, 193: 104603.

[12] Li Y F, Huang J, Li Z, et al. Atmospheric pollution revealed by trace elements in recent snow from the central to northern Tibetan Plateau[J]. Environmental Pollution, 2020, 263(Part A): 109109.

[13] Dong Z W, Ren J W, Qin D H, et al. Chemistry characteristics and environmental significance of snow deposited on the Laohugou Glacier No. 12, Qilian Mountains[J]. Journal of Glaciology and Geocryology, 2013, 3(2): 327-335.

[14] Zhong Y T, Liu X C, Fan Z A, et al. Chemical characteristics and source assessment of atmospheric precipitation in Urumqi[J]. Desert and Oasis Meteorology, 2016, 10(6): 81-87.

[15] Zhong Y T, Liu X C, He Q, et al. Chemical characteristics and source assessment of atmospheric precipitation at Yining, Xinjiang[J]. Desert and Oasis Meteorology, 2016, 10(3): 77-82.

[16] Chen T Q, Rao W B, Jin K, et al. Chemical characteristics and major ion sources of precipitation in the Alxa Desert Plateau[J]. Research of Environmental Sciences, 2018, 31(12): 2083-2093.

[17] Jia W X, Li C W. Chemical properties of summer precipitation in the Yushugou River Basin in the East Tianshan Mountains[J]. Arid Zone Research, 2018, 35(2): 277-286.

[18] Wang X Y, Jiang Z X. Hydrochemical characteristics and sources of ions in precipitation at the East Qilian Mountains[J]. Environmental Science, 2016, 37(9): 3322-3332.

[19] Han H D, Wang J, Wei J F, et al. Backwasting rate on debris-covered Koxkar glacier, Tuomuer mountain, China[J]. Journal of Glaciology, 2010, 56: 287-296.

[20] Sun J Y, Qin D H, Ren J W, et al. A study of water chemistry and aerosol at the headwaters of the Urumqi River in the Tianshan Mountains[J]. Journal of Glaciology and Geocryology, 2002, 24(2): 186-191.

[21] Zhao Q D, Ye B S, Ding Y J, et al. Hydrological process of a typical catchment in cold region: simulation and analysis[J]. Journal of Glaciology and Geocryology, 2011, 33(3): 595-605.

[22] Han H D, Liu S Y, Ding Y J, et al. Near surface meteorological characteristics on the Koxkar Baxi Glacier, Tianshan[J]. Journal of Glaciology and

Geocryology, 2008, 30(6): 967-975.

[23] Song Y G, Zong X L, Li Y, et al. Loess sediments and rapid climate oscillation during the last glacial period in the westerlies-dominated Central Asia[J]. Quaternary Sciences, 2019, 39(3): 535-548.

[24] Xiao Z M, Li P, Chen K, et al. Characteristics and sources of chemical composition of atmospheric precipitation in Tianjin[J]. Research of Environmental Sciences, 2015, 28(7): 1025-1030.

[25] Keene W C, Pszenny A, Galloway J N, et al. Sea salt corrections and interpretation of constituent ratios in marine precipitation[J]. Journal of Geophysical Research: Atmospheres, 1986, 91(D6): 6647-6658.

[26] Xiao H, Shen Z L, Huang M Y. Chemical characteristics of tropical Western Pacific precipitation[J]. Acta Scientiae Circumstantiae, 1993, 13(2): 143-149.

[27] Li X G, Zhao L J, Liu Q, et al. Chemical composition of precipitation and its sources in Shangluo City of Qilin mountainous area[J]. Journal of Water Resources & Water Engineering, 2020, 31(4): 24-30.

[28] Hou S G. Chemical characteristics of precipitation at the headwaters of the Urumqi River in the Tianshan Mountains[J]. Journal of Glaciology and Geocryology, 2001, 23(1): 80-84.

[29] Mountaineering expedition team of the Chinese Academy of Sciences. Geology and paleontology of Tuomuerfeng area in Tianshan Mountains[M]. Urumqi: Xinjiang People' s Publishing House, 1985.

[30] Li T, Ni S B. Element abundances of the crust and lithosphere in Tarim-North China plate[J]. Geology and Prospecting, 1998, 34(1): 20-24.

[31] Zhang L Y, Qiao B Q, Wang H B, et al. Chemical characteristics of precipitation in a typical urban site of the Hinterland in Three Gorges Reservoir, China[J]. Journal of Chemistry, 2018, 2018: 109109.

[32] Cerqueira M R, Pinto M F, Derossi I N, et al. Chemical characteristics of rainwater at a southeastern site of Brazil[J]. Atmospheric Pollution Research, 2014, 5: 253-261.

[33] Marrugo Negrete J, Pinedo Hernández J, Díez S. Assessment of heavy metal pollution, spatial distribution and origin in agricultural soils along the Sinú River Basin, Colombia[J]. Environmental Research, 2017, 154: 380-388.

[34] Kumar A, Tiwari S, Verma A, et al. Tracing isotopic signatures (δD and δ^{18}O) in precipitation and glacier melt over Chorabari Glacier: Hydroclimatic inferences for the Upper Ganga Basin (UGB), Garhwal Himalaya[J]. Journal of Hydrology: Regional Studies, 2018, 15: 68-89.

[35] Du Z H, Xiao C D, Wang Y Z, et al. Dust provenance in Pan-third pole modern glacierized regions: What is the regional source?[J]. Environmental Pollution, 2019, 250: 762-772.

[36] Wang X, Carrapa B, Sun Y, et al. The role of the westerlies and orography in Asian hydroclimate since the late Oligocene[J]. Geology, 2020, 48: 1-5.

[37] Zhang D, Huang X Y, Li C J. Natural and anthropogenic factors controlling river water hydrochemical evolution[J]. Journal of Arid Land Resources and Environment, 2012, 26(12): 75-80.

[38] Huang S C, Wortmann M, Duethmann D, et al. Adaptation strategies of agriculture and water management to climate change in the Upper Tarim River basin, NW China[J]. Agricultural Water Management, 2018, 203: 207-224.

[39] Tao H, Mao W Y, Huang J L, et al. Drought and wetness variability in the Tarim river basin and possible associations with large scale circulation[J]. Advances in Water Science, 2014, 25(1): 45-52.

[40] Wang J, Han H D, Xu J L, et al. Hydrochemical characteristics of the mountain runoff in Tarim River Basin, China[J]. China Environmental Science, 2021, 41(4): 1576-1587.

[41] Du W T, Kang S C, Qin X, et al. Can summer monsoon moisture invade the Jade Pass in Northwestern China?[J]. Climate Dynamics, 2020, 55: 3101-3115.

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