Postprint: Geodetector-Based Analysis of Spatial Variation Characteristics of Precipitation δ^{18}O in the Tibetan Plateau

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Abstract

Geographical Detector is a statistical method for studying the spatial stratified heterogeneity of geographical phenomena and quantitatively analyzing their driving factors. Using the Geographical Detector method, the annual mean precipitation $ $18O values at 24 sites on the Tibetan Plateau were analyzed. This method can, to a certain extent, reflect the spatial stratified heterogeneity of annual mean precipitation $ $18O values on the Tibetan Plateau. The results show that the explanatory power of latitude, altitude, longitude, and precipitation amount for the spatial stratified heterogeneity of annual mean precipitation $ $18O values on the Tibetan Plateau is 0.82, 0.71, 0.57, and 0.49, respectively; the explanatory power of temperature for the spatial stratified heterogeneity of annual mean precipitation $ $18O values is not significant; the interaction between factors enhances the spatial stratified heterogeneity of annual mean precipitation $ $18O values. The relationships between annual mean precipitation $ $18O values at sites on the Tibetan Plateau and latitude, longitude, altitude, annual precipitation amount, and annual mean temperature are discussed, and the seasonal variation of the dominant controlling factors of precipitation $ $18O is analyzed. It is concluded that latitude has the strongest explanatory power for the spatial stratified heterogeneity of annual mean, summer mean, and winter mean precipitation $ $18O values on the Tibetan Plateau.

Full Text

Preamble

Spatial Heterogeneity of Annual Precipitation δ^{18}O over the Tibetan Plateau Based on the Use of a Geographical Detector

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Abstract: The geographical detector is a statistical method for studying the spatial heterogeneity of geographic phenomena and quantitatively analyzing their driving factors. This method was applied to analyze the annual mean precipitation δ^{18}O from multiple stations on the Tibetan Plateau. The results successfully reflect the spatial heterogeneity of annual precipitation δ^{18}O over the Tibetan Plateau, revealing that latitude, altitude, longitude, and precipitation amount explain [values missing] of the spatial variation in annual precipitation δ^{18}O, while temperature shows no significant explanatory power. Interactions between factors enhance the spatial heterogeneity of annual precipitation δ^{18}O. The relationships between annual precipitation δ^{18}O and latitude, longitude, altitude, annual precipitation, and mean temperature are discussed, and seasonal variations in the dominant controlling factors are analyzed. Latitude demonstrates the strongest explanatory power for the spatial heterogeneity of annual, summer mean, and winter mean precipitation δ^{18}O over the Tibetan Plateau.

Keywords: Tibetan Plateau; precipitation δ^{18}O; spatial heterogeneity; geographical detector

Introduction

Stable isotopes in water bodies (δ^{18}O) serve as effective environmental tracers. Dansgaard established the Global Network of Isotopes in Precipitation (GNIP) and discovered relationships between precipitation isotopes and factors such as temperature, precipitation amount, and altitude. Subsequent research has extensively investigated the climatic and environmental significance of precipitation δ^{18}O, demonstrating temperature effects, latitude effects, continental effects, and altitude effects, as well as influences from moisture source regions and regional convective activity. Since the 1990s, Chinese scientists initiated the Tibetan Plateau Network of Isotopes in Precipitation (TNIP) to support ice core research on the plateau. TNIP has conducted multi-year continuous monitoring of precipitation isotopes at over 20 stations, providing a theoretical foundation for interpreting ice core records and studying hydrological cycles in the region. Based on this program, scholars have gained deeper understanding of the spatiotemporal patterns and controlling factors of precipitation δ^{18}O on the Tibetan Plateau, revealing that the northern and southern plateau are controlled by westerly circulation and Indian monsoon circulation, respectively. Precipitation δ^{18}O shows higher values in the north than in the south during summer, and the opposite pattern during winter.

The geographical detector method, proposed by Wang Jinfeng et al., is fundamentally based on variance analysis. By comparing within-layer and between-layer variances of categorical or numerical data, it quantitatively investigates spatial heterogeneity of geographic phenomena and interactions between controlling factors. Compared with other spatial heterogeneity research methods, the geographical detector offers higher explanatory power and has been successfully applied to studies of disease transmission patterns, land use change, and geographic boundary delineation.

Building upon previous research, this study analyzes spatial heterogeneity of precipitation δ^{18}O on the Tibetan Plateau using multi-year precipitation δ^{18}O data from 24 observation stations combined with the geographical detector method. The objective is to quantitatively investigate how different influencing factors explain the spatial variation of precipitation δ^{18}O and discuss possible relationships between annual precipitation δ^{18}O and latitude, longitude, altitude, annual precipitation, and mean temperature, as well as seasonal variations in dominant controlling factors.

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1. Methods

1.1 Data

The primary dependent variable in this study is the annual mean precipitation δ^{18}O from 24 stations on the Tibetan Plateau. The independent variables are station latitude, longitude, altitude, mean annual temperature, and mean annual precipitation amount.

The precipitation δ^{18}O dataset comprises two parts: (1) data from 8 stations obtained from GNIP as event-scale precipitation isotope observations, and (2) data from 16 stations from the National Tibetan Plateau Data Center (http://data.tpdc.ac.cn/zh-hans/) as monthly mean precipitation isotope observations. All data are accessible online, and Table 1 summarizes basic information for these stations.

Precipitation samples collected before 2010 were analyzed at the Key Laboratory of Cryosphere and Environment, Chinese Academy of Sciences, using a MAT-252 gas mass spectrometer with a precision of $±$0.2‰. Samples collected after 2010 were analyzed at the Key Laboratory of Tibetan Environment Changes and Land Surface Process, Institute of Tibetan Plateau Research, using a MAT-253 mass spectrometer with the same precision. All δ^{18}O values were calibrated against VSMOW. Temperature and precipitation data for each station were also obtained from the respective databases, with annual means calculated from monthly data. For TNIP stations, annual temperature and precipitation data were derived from observations at nearby meteorological stations.

1.2 Geographical Detector Method

The geographical detector method is essentially an analysis of variance. It quantitatively expresses spatial heterogeneity and interactions between controlling factors by comparing within-layer and between-layer variances. The factor detector quantifies the explanatory power of each factor for precipitation δ^{18}O spatial heterogeneity using the q-statistic:

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N\sigma^2}$$

where q represents the explanatory power of a factor for precipitation δ^{18}O spatial heterogeneity, with values ranging from [0,1]. A larger q value indicates stronger explanatory power, where $q = 1$ means the factor completely controls the spatial distribution of precipitation δ^{18}O, and $q = 0$ indicates no relationship. L represents the number of strata or classifications for the factor, N and N_h are the sample sizes for the entire region and the h-th layer, respectively, and σ^2 and *σ_h^2* are the variances of precipitation δ^{18}O for the entire region and the h-th layer.

The interaction detector identifies whether the interaction between two factors enhances or weakens their explanatory power. Interaction relationships are redefined based on whether the combined q-statistic is greater than, less than, or equal to the sum or maximum of individual factor q-statistics.

1.3 Calculation Steps

Annual precipitation δ^{18}O values for each station were calculated as precipitation-weighted means, representing the average state during the study period. Seasonal means were similarly computed by weighting summer (June-August) and winter (December-February) precipitation δ^{18}O data by precipitation amount. All weighted averages used arithmetic weighting.

To discuss influencing factors on precipitation δ^{18}O in different regions, stations were divided into southern and northern plateau groups using the Naqu station as the boundary. The seasonal amplitude (summer mean minus winter mean) was calculated for each station, with negative values north of Naqu (winter > summer) and positive values south of Naqu (summer > winter).

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2. Results

2.1 Spatial and Temporal Distribution of Precipitation δ^{18}O on the Tibetan Plateau

As shown in Figure 2, annual mean precipitation δ^{18}O is higher in the northern plateau and lower in the southern plateau. Mean annual temperature is highest in the south, lowest in the central region, and intermediate in the north. Annual precipitation decreases from south to north across the plateau. Seasonally, winter mean precipitation δ^{18}O exceeds summer mean in the southern plateau, while the opposite occurs in the northern plateau, consistent with previous research. Spatially, the annual mean pattern closely resembles the summer mean pattern, likely because summer precipitation contributes most significantly to the annual total.

2.2 q-Statistics of Individual Factors

Table 3 presents the explanatory power of each factor for spatial heterogeneity of annual mean precipitation δ^{18}O. Latitude shows the strongest control, with a *q*-statistic of [value missing], followed by altitude ([value missing]), longitude ([value missing]), and precipitation amount ([value missing]). Temperature demonstrates no significant explanatory power for spatial heterogeneity of annual mean precipitation δ^{18}O.

2.3 Interactive q-Statistics of Factors

Interaction analysis reveals that pairwise combinations of latitude, longitude, altitude, and precipitation amount, as well as temperature-altitude and temperature-latitude interactions, show dual-factor enhancement effects on spatial heterogeneity of annual mean precipitation δ^{18}O. Temperature-precipitation and temperature-longitude interactions exhibit non-linear enhancement. The latitude-precipitation interaction achieves the highest explanatory power at [value missing], followed by latitude-altitude ([value missing]), latitude-temperature ([value missing]), longitude-temperature ([value missing]), longitude-precipitation ([value missing]), altitude-temperature ([value missing]), and temperature-precipitation ([value missing]). These results demonstrate that factor interactions significantly enhance spatial heterogeneity of annual precipitation δ^{18}O.

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3. Dominant Controlling Factors for Spatial Heterogeneity of Precipitation δ^{18}O

3.1 Relationship Between Annual Mean δ^{18}O and Latitude/Precipitation

Geographical detector analysis shows latitude explains over [value missing] of spatial heterogeneity in plateau precipitation δ^{18}O, with the latitude-precipitation interaction reaching [value missing]. This reflects different climate modes and moisture transport characteristics from south to north. The Tibetan Plateau exhibits westerly, monsoon, and transitional modes that determine spatiotemporal patterns of precipitation stable isotopes. Southern plateau precipitation isotopes are primarily controlled by warm, moist air from the Indian monsoon, while northern plateau variations are dominated by high-latitude oceanic or continental moisture from westerlies.

Correlation analysis between annual precipitation δ^{18}O and precipitation amount across all stations shows no significant relationship (δ^{18}O = -0.01P + [intercept], p = 0.08, where P is precipitation in mm). However, regional analysis reveals a significant positive correlation in the southern plateau (δ^{18}O = 0.013P + [intercept], R^2 = 0.46, $p < 0.05$) but not in the northern plateau. This positive correlation in the southern plateau reflects the continental effect —distance from the primary moisture source—as maritime air masses move inland, undergo moist adiabatic cooling, and experience increased fractionation, resulting in lower δ^{18}O values.

3.2 Relationship Between Annual Mean δ^{18}O and Altitude

Geographical detector results indicate altitude explains [value missing] of spatial heterogeneity, second only to latitude, confirming its important role in driving precipitation δ^{18}O spatial variation. Previous studies have documented altitude effects across different plateau regions. For example, Sun et al. found a significant altitude effect in the northwestern plateau (δ^{18}O = -0.00126h - 9.01, R^2 = 0.82, where h is altitude in meters), with a vertical lapse rate of -0.126‰ (100m)$^{-1}$. Wen et al. reported a lapse rate of -0.27‰ (100m)$^{-1}$ on the southern Himalayan slopes. Using data from 24 stations across the entire plateau, this study finds a significant negative correlation between annual precipitation δ^{18}O and altitude (δ^{18}O = -0.0027h + [intercept], R^2 = 0.65, $p < 0.001$), with a vertical lapse rate of -0.27‰ (100m)$^{-1}$, approaching the global average. This may relate to the spatial representativeness of selected stations, as our 24-station dataset better represents the entire plateau.

3.3 Relationship Between Annual Mean δ^{18}O and Temperature

According to Rayleigh fractionation theory, when moisture source and mixing processes have minimal influence, precipitation δ^{18}O should correlate positively with saturated temperature along transport paths. Studies of atmospheric water vapor in Tashkurgan suggest year-round Rayleigh fractionation control. However, other research indicates that moisture in the northern plateau during spring and autumn mixes with local evapotranspiration, while summer moisture sources are complex, incorporating westerly, recycled, and small amounts of southeast monsoon moisture, with westerly moisture dominating only in winter.

Geographical detector analysis shows temperature has no significant explanatory power for annual mean precipitation δ^{18}O spatial heterogeneity. Regional analysis reveals a significant positive correlation in the northern plateau (δ^{18}O = 0.51T + [intercept], R^2 = 0.52, $p < 0.05$, where T is mean annual temperature in °C) but not in the southern plateau. This spatial temperature effect in the northern plateau may relate to local evaporation, as higher temperatures increase evaporative enrichment of precipitation $\delta^{18}O$.

3.4 Seasonal Variation of Dominant Controlling Factors

Table 5 shows seasonal variations in factor explanatory power. The dominant factor for summer precipitation $\delta^{18}O$ spatial heterogeneity is similar to the annual pattern, with latitude showing the strongest control. This likely reflects that summer precipitation $\delta^{18}O$ values dominate the annual mean. During summer, southern plateau precipitation is controlled by Indian monsoon moisture while northern precipitation is controlled by westerly moisture. In winter, the entire plateau is influenced by westerly moisture, but the southern branch of the westerly jet is closer to the Bay of Bengal and Arabian Sea, potentially explaining why winter $\delta^{18}O$ values are higher in the south than north, reflecting different moisture source influences.

Longitude shows stronger explanatory power for summer (q = [value missing]) than annual mean (q = [value missing]) precipitation $\delta^{18}O$. Summer precipitation $\delta^{18}O$ is highest in the west, lowest in the center, and intermediate in the east. Since western and eastern stations are located further north, longitude' s explanatory power may actually reflect the latitudinal pattern of different moisture transport processes between the northern and southern plateau.

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4. Conclusion

Based on precipitation-weighted $\delta^{18}O$ data from 24 observation stations across the Tibetan Plateau, geographical detector analysis reveals that latitude, altitude, longitude, and precipitation amount explain [values missing], respectively, of spatial heterogeneity in annual precipitation $\delta^{18}O$, while temperature shows no significant effect. Interactions between factors consistently enhance explanatory power, with the latitude-precipitation interaction strongest at [value missing]. These interactions amplify spatial heterogeneity of annual, summer, and winter precipitation $\delta^{18}O$. Latitude consistently emerges as the dominant controlling factor for spatial heterogeneity of precipitation $\delta^{18}O$ across annual, summer, and winter timescales.

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References

[1] Dansgaard W. Stable isotopes in precipitation[J]. Tellus, 1964, 16(4): 436-468.

[2] Gao Jing, Masson-Delmotte V, Risi C, et al. What controls precipitation δ^{18}O in the southern Tibetan Plateau at seasonal and intra-seasonal scales? A case study at Lhasa and Nyalam[J]. Tellus Series B: Chemical and Physical Meteorology, 2013, 65: 21043.
[3] Gao Jing, Tian Lide, Liu Yongqin, et al. Oxygen isotope variation in the water cycle of the Yamzho lake Basin in southern Tibetan Plateau[J]. Chinese Science Bulletin, 2009, 54(15): 2153-2159.
[4] Duan Keqin, Yao Tandong, Wang Ninglian, et al. The difference in precipitation variability between the North and South Tibetan Plateaus[J]. Journal of Glaciology and Geocryology, 2008, 30(5): 726-732.
[5] Tian Lide, Yao Tandong, Yu Wusheng, et al. Stable isotopes of precipitation and ice core on the Tibetan Plateau and moisture transports[J]. Quaternary Sciences, 2006, 26(2): 145-152.
[6] Wang Jinfeng, Xu Chengdong. Geodetector: Principle and prospective[J]. Acta Geographica Sinica, 2017, 72(1): 116-134.
[7] Liu Jianrong, Song Xianfang, Yuan Guofu, et al. Stable isotopic compositions of precipitation in China[J]. Tellus Series B: Chemical and Physical Meteorology, 2014, 66: 22569.
[8] Yao Tandong, Masson-Delmotte V, Gao Jing, et al. A review of climatic controls on δ^{18}O in precipitation over the Tibetan Plateau: Observations and simulations[J]. Reviews of Geophysics, 2013, 51: 525-548.
[9] Zhang Xinping, Yao Tandong, Nakawo M, et al. Meridional variation of stable isotopic compositions in precipitation of the Tibetan Plateau and its adjacent regions[J]. Journal of Glaciology and Geocryology, 2002, 24(3): 245-253.
[10] Sun Congjian, Zhang Ziyu, Li Jie, et al. Temporal and spatial characteristics of stable isotopes of atmospheric precipitation in the Northwestern Tibetan Plateau[J]. Mountain Research, 2018, 36(2): 217-228.
[11] Yu Wusheng, Ma Yaoming, Sun Weizhen, et al. Climatic significance of δ^{18}O records from precipitation on the western Tibetan Plateau[J]. Chinese Science Bulletin, 2009, 54(15): 2131-2139.
[12] Tian Lide, Yao Tandong, Sun Weizhen, et al. Stable isotope variation of precipitation in the middle of Qinghai-Xizang Plateau and monsoon activity[J]. Geochimica, 2001, 30(3): 217-222.
[13] Tian Lide, Weng Yongbiao, et al. The altitude effect of δ^{18}O in precipitation and river water in the Southern Himalayas[J]. Chinese Science Bulletin, 2012, 57(12): 1053-1059.
[14] He You, Gao Jing, Yao Tandong, et al. Spatial distribution of stable isotope in precipitation upon the Tibetan Plateau analyzed with various interpolation methods[J]. Journal of Glaciology & Geocryology, 2015, 37(2): 351-359.
[15] Tian Lide, Yao Tandong. High-resolution climatic and environmental records from the Tibetan Plateau ice cores[J]. Chinese Science Bulletin, 2016, 61(9): 926-937.
[16] Rowley D B, Pierrehumbert R T, Currie B S. A new approach to stable isotope based paleoaltimetry: Implications for paleoaltimetry and paleohypsometry of the High Himalaya since the Late Miocene[J]. Earth and Planetary

Science Letters, 2001, 188(1-2): 1-14.
[17] Yang X, Yao T. Seasonality of moisture supplies to precipitation over the Third Pole: A stable water isotopic perspective[J]. Scientific Reports, 2020, 10(1): 15020.
[18] Adhikari N, Gao J, Yao T D, et al. The main controls of the precipitation stable isotopes at Kathmandu, Nepal[J]. Tellus Series B: Chemical and Physical Meteorology, 2020, 72(1): 1-17.
[19] He Y, Risi C, Gao J, et al. Impact of atmospheric convection on south Tibet summer precipitation isotopologue composition using a combination of in situ measurements, satellite data, and atmospheric general circulation modeling[J]. Journal of Geophysical Research: Atmospheres, 2015, 120(9): 3852-3871.
[20] Ren W, Yao Tandong, Yang Xiaoxin, et al. Implications of variations in δ^{18}O and δD in precipitation at Madoi in the eastern Tibetan Plateau[J]. Quaternary International, 2013, 313-314: 56-61.
[21] Joswiak D R, Yao Tandong, Wu Guangjian, et al. Ice core evidence of westerly and monsoon moisture contributions in the central Tibetan Plateau[J]. Journal of Glaciology, 2013, 59(213): 56-66.
[22] Chakraborty S, Sinha N, Chattopadhyay R, et al. Atmospheric controls on the precipitation isotopes over the Andaman Islands, Bay of Bengal[J]. Scientific Reports, 2016, 6: 19555.
[23] Dong W, Lin Y, Wright J S, et al. Summer rainfall over the southwestern Tibetan Plateau controlled by deep convection over the Indian subcontinent[J]. Science Foundation in China, 2016, 7: 19.
[24] Guenther F, Aichner B, Siegwolf R, et al. A synthesis of hydrogen isotope variability and its hydrological significance at the Qinghai-Tibetan Plateau[J]. Quaternary International, 2013, 313: 3-16.
[25] Zeng Di, Wu Jinkui, Li Hongyuan, et al. Hydrogen and oxygen isotopes in precipitation in the arid regions of Northwest China: A review[J]. Arid Zone Research, 2020, 37(4): 857-869.
[26] Sun Congjian, Zhang Ziyu, Chen Wei, et al. Spatial distribution of precipitation stable isotopes in the alpine zones in Central Asia[J]. Arid Zone Research, 2019, 36(1): 19-28.
[27] Zhang Yaning, Zhang Mingjun, Wang Shengjie, et al. Water vapor sources of short time heavy rainfall in Xinjiang based on specific humidity adjusted Lagrangian model[J]. Arid Zone Research, 2019, 36(3): 698-711.
[28] Ma Q, Zhang M, Wang S, et al. Contributions of moisture from local evaporation to precipitations in Southeast China based on Hysplit4 trajectory model[J]. Journal of Arid Land Resources and Environment, 2016, 30(7): 151-156.
[29] Wang S, Jiao R, Zhang M, et al. Changes in below-cloud evaporation affect precipitation isotopes during five decades of warming across China[J]. Journal of Geophysical Research: Atmospheres, 2021, 126(7): e2020JD033075.
[30] Wang S, Zhang M, Che Y, et al. Contribution of recycled moisture to precipitation in oases of arid Central Asia: A stable isotope approach[J]. Water Resources Research, 2016, 52(4): 3246-3257.

[31] Wang S, Zhang M, Che Y, et al. Influence of below-cloud evaporation on deuterium excess in precipitation of arid Central Asia and its meteorological controls[J]. Journal of Hydrometeorology, 2016, 17(7): 1973-1984.
[32] Wang S, Zhang M, Hughes C E, et al. Factors controlling stable isotope composition of precipitation in arid conditions: An observation network in the Tianshan Mountains, Central Asia[J]. Tellus Series B: Chemical and Physical Meteorology, 2016, 68(Suppl.): 289-302.

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