Distribution Patterns and Genesis of Glaciers on the Qinghai-Tibet Plateau Based on Terrain Gradients: Postprint

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Abstract

Currently, uncertainties remain in the mechanisms influencing glacier distribution and change. To investigate the effects of terrain factors on glacier distribution patterns, this study employs the 6th version of the Randolph Glacier Inventory data and NASADEM as data sources, utilizing methods including the mean change point method, distribution index, and geographical detector to analyze the distribution patterns of glaciers on the Tibetan Plateau across terrain gradients (including terrain relief, elevation, slope, and aspect) and their response relationships with terrain factors. The results indicate that: (1) Glaciers on the Tibetan Plateau exhibit wide suitability for aspect and slope, but strong selectivity for terrain relief and elevation, with dominant distribution occurring at high terrain relief and high elevation. (2) Terrain significantly influences glacier development, with the effects of various terrain factors on glacier spatial distribution being markedly different. Elevation and terrain relief are the primary factors controlling glacier distribution, and interaction detection results demonstrate that their combined effect exerts the greatest influence on spatial differentiation of glaciers. (3) Along elevation and terrain relief gradients, Himalayan glaciers display the widest range of dominant distribution, followed by Karakoram glaciers; the dominant distributions of glaciers in the remaining ten mountain ranges all follow an approximately normal distribution, though with distinct morphological characteristics across different ranges.

Full Text

Distribution Pattern and Causes of Glaciers in the Tibetan Plateau Based on Terrain Gradient

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Abstract

The mechanisms influencing glacier distribution and change remain uncertain. To investigate the impact of topographic factors on glacier distribution patterns, this study employs Randolph Glacier Inventory data and NASADEM as data sources, utilizing mean change-point analysis, distribution index, and geodetector methods to analyze the distribution patterns of glaciers across terrain gradients (including relief degree of land surface, altitude, slope, and aspect) and their response relationships with topographic factors in the Tibetan Plateau. The results indicate that: (1) Glaciers in the Tibetan Plateau exhibit broad suitability for aspect and slope, but strong selectivity for relief degree and altitude, with dominant distribution at high relief degrees and high altitudes. (2) Terrain significantly influences glacier development, with different topographic factors having distinct effects on glacier spatial distribution. Altitude and relief degree are the primary factors controlling glacier distribution, and interactive detection results show that their combined effect has the greatest impact on spatial heterogeneity. (3) Along altitude and relief degree gradients, the Himalayas show the most extensive dominant glacier distribution range, followed by the Karakoram Mountains, while the remaining ten mountain ranges display approximately normal distribution patterns, though with distinct morphological characteristics.

Keywords: glacier distribution; terrain gradient; distribution index; geodetector; Tibetan Plateau

1 Study Area and Data Sources

1.1 Study Area Overview

The Tibetan Plateau is the highest and largest inland plateau in the world. Its unique conditions of high elevation, low temperature, and large diurnal temperature variation are highly conducive to glacier development. As the center of modern glacier activity in mid-low latitudes, the plateau also serves as a regulator of environmental change across Asia and even the Northern Hemisphere. The plateau boundary is based on the Zhang RGI 6.0 青藏高原界线, extending from the southern foothills of the Himalayas in the south to the northern foothills of the Pamir Plateau, Kunlun Mountains, and Qilian Mountains in the north, from the western edges of the Hindu Kush Mountains and Pamir Plateau in the west to the eastern edges of the Qilian and Hengduan Mountains in the east, covering a total area of 308.34$\times10^{4}$ km^2 with a general elevation that decreases from west to east. The marginal mountains exhibit significant relief, while the interior Qaidam Basin and Qiangtang Plateau show relatively minor undulation. The Tibetan Plateau, known as the "Asian Water Tower," contains glaciers that are particularly sensitive to climate change due to their location in high-altitude, low-latitude regions. According to RGI 6.0 data, the plateau hosts approximately 49,800 glaciers covering 8.3$×10^{4}$ km^2. This study divides all glaciers in the region into 14 mountain glacier systems based on the Randolph Glacier Inventory and the Second Chinese Glacier Inventory, with the Karakoram glacier division also referencing previous research.

1.2 Data Sources

Glacier data were obtained from the Randolph Glacier Inventory version 6.0 (RGI 6.0) published by the National Snow and Ice Data Center (http://www.glims.org/RGI/). This version improves the proportion of glaciers with clear temporal information, incorporates regional glacier inventories, and refines the delineation of glacierized areas. Topographic data were derived from NASADEM, provided by NASA (https://earthdata.nasa.gov/) at 30-meter spatial resolution as an upgraded version of SRTM data. Using ArcGIS software, we extracted four topographic factors: relief degree of land surface (RDLS), altitude, slope, and aspect.

2 Research Methods

2.1 Calculation of Relief Degree of Land Surface

The relief degree of land surface characterizes elevation undulation and exhibits scale dependence in its calculation, making the determination of an optimal analysis window crucial. The RDLS calculation formula is:

$$RDLS = \frac{ALT}{1000} + \frac{[Max(H) - Min(H)]}{500}$$

where RDLS is the relief degree of land surface; ALT, Max(H), and Min(H) represent the mean altitude, maximum altitude, and minimum altitude within the optimal analysis window, respectively; and A is the total area of the region (excluding areas with relative elevation difference <30 m).

We employed the mean change-point method to determine the optimal analysis window. First, using ArcGIS software, we calculated the mean elevation difference under various analysis windows (from 2$×2to121×$121 pixels). Then we computed the unit relief intensity (T) using:

$$T_k = \frac{t_k}{s_k}$$

where T_k is the unit relief intensity for the k-th analysis window, t_k is the mean elevation difference, and s_k is the analysis window area. Taking the logarithm of sequence T yields a nonlinear series sample X_i (i = 1, 2, 3, ···, 120). Dividing X_i into two segments ($X_1, ..., X_i$ and $X_{i+1}, ..., X_{120}$), we calculated the total sample variance (S) and the sum of variances for the two segments (S_i). The analysis window corresponding to the maximum difference ($S - S_i$) represents the optimal window. Based on NASADEM data, the mean change-point method determined the optimal RDLS analysis window for the Tibetan Plateau as a 36$\times$36 pixel rectangular neighborhood, corresponding to approximately 1.17 km^{2}.

2.2 Distribution Index

The standardized, dimensionless distribution index eliminates the influence of different terrain factor classifications and glacier area differences among mountain ranges, accurately and objectively revealing the deviation between actual and standard glacier distributions across various mountain ranges on the Tibetan Plateau. The calculation formula is:

$$P(A) = \frac{S_{ie}/S_i}{S_e/S}$$

where P represents the distribution index; e represents the terrain factor; S_{ie} represents the glacier area of the i-th mountain range under a specific class of terrain factor e; S_i represents the total glacier area of the i-th mountain range; S represents the total study area; and S_e represents the total area under a specific class of terrain factor e.

The distribution index value indicates glacier distribution patterns: when $P > 1$, glaciers show dominant distribution, suggesting suitable conditions for glacier survival or development in that terrain zone; when $P < 1$, glaciers show recessive distribution, indicating unsuitable conditions. The degree of dominance increases with higher P values, while recessiveness intensifies with lower values. Additionally, a relatively flat distribution curve with minor fluctuations indicates broad suitability to terrain differences, whereas a highly variable curve suggests strong selectivity for terrain, with more extensive glacier development in preferred terrain classes.

2.3 Geodetector

Geodetector is a novel statistical method for detecting spatial stratified heterogeneity and revealing underlying driving factors. Its factor detection q-statistic measures spatial heterogeneity and identifies explanatory factors:

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

where q is the explanatory power of the driving factor; L represents the stratification of independent or dependent variables; N_h and N are the numbers of units in layer h and the entire region, respectively; and σ_h^2 and σ^2 are the variances of the driving factor and glacier distribution. The q value ranges from [0,1], with larger values indicating stronger explanatory power of the driving factor on glacier distribution. In extreme cases, q = 1 indicates complete control of glacier spatial distribution by the driving factor, while q = 0 indicates no relationship.

3 Results

3.1 Glacier Distribution Patterns Based on Terrain Gradients

To investigate glacier distribution characteristics across various terrain factors, we classified RDLS (0.3989–11.5973) and altitude (878–781 m) into 10 levels using the natural breaks method, slope (0°–86.3963°) into 10 levels, and aspect into 9 categories (flat, north, northeast, east, southeast, south, southwest, west, northwest). We then calculated distribution indices for glaciers across these terrain gradients.

The results show that glacier distribution curves for RDLS and altitude exhibit substantial variation, with distribution indices increasing as RDLS and altitude rise. Glaciers show dominant distribution in RDLS class 5 (5.0795–11.5973) and altitude class 5 (5082–8781 m), indicating strong selectivity for these factors. In contrast, distribution curves for aspect and slope are relatively flat, showing broad suitability. Glaciers exhibit dominant distribution on north, northeast, east, and northwest aspects, with the highest index on north-facing slopes, followed by northeast-facing slopes. Glaciers show the broadest suitability for slope, with distribution indices concentrated around the standard value in slope class 1 (5.0623°–36.1110°), and increasing trends as slopes steepen.

3.2 Quantitative Analysis of Topographic Influence

Geodetector factor detection clarifies the influence of terrain factors on glacier distribution heterogeneity. Using ArcGIS, we created 2 km$×$2 km sampling grids covering the entire Tibetan Plateau and selected grids within 2 km of glaciers, totaling 67,234 grids. We calculated the percentage of glacier area in each grid as the dependent variable Y, assigned to grid centers, and used altitude, RDLS, slope, and aspect as independent variables X. Factor and interactive detection results are presented in Table 1.

The results reveal that q values for altitude and RDLS across all mountain ranges far exceed those for slope and aspect. Except for the Qiangtang Plateau and Gangdise Mountains, all mountain ranges show q(altitude) > q(RDLS) characteristics. The small q values for slope and aspect indicate their relatively weak influence on glacier spatial distribution. Altitude and RDLS emerge as the dominant factors controlling glacier distribution across the Tibetan Plateau.

Interactive detection results show that terrain factors do not independently influence glacier distribution patterns; any two-factor interaction exceeds single-factor effects, demonstrating dual-factor enhancement and nonlinear amplification without any independent or weakening relationships. The combined effect of altitude and RDLS shows the greatest impact on glacier spatial heterogeneity. Although slope and aspect have low individual q values, their interactions with other factors exceed single-factor effects, making their influence non-negligible.

3.3 Distribution Characteristics of Glaciers in Various Mountain Ranges Along RDLS and Altitude Gradients

To further investigate distribution characteristics, we classified RDLS and altitude into 20 equal-interval levels and calculated distribution indices for each mountain range along these gradients.

Along the RDLS gradient, mountain ranges display distinct patterns. The Himalayas, Karakoram, and Pamir show dominant distribution across more than 10 intervals, with high index values in their dominant zones. The Himalayas exhibit the broadest dominant distribution range (RDLS 5.3262–11.3733), with indices increasing as RDLS increases. The Karakoram shows the second broadest range (5.3262–11.5973), with indices first increasing then sharply decreasing. The Hindu Kush, Hengduan, and Nyainqentanglha ranges show dominant distribution across 17–20 intervals with flat distribution curves. The Kunlun, Gangdise, Tanggula, Altun, Qilian, and Qiangtang ranges show dominant distribution across fewer than 10 intervals with tall, narrow normal distribution curves. The Qilian Mountains show the narrowest dominant distribution, spanning only 4 intervals.

[Figure 4: see original paper]

Along the altitude gradient, glacier area distribution patterns vary significantly among mountain ranges. The Himalayas show the broadest dominant distribution range (altitude classes 23–49, 5048–8781 m), with indices increasing sharply then stabilizing with rising altitude. The Karakoram also shows a broad dominant range (classes 30–40, 5048–8611 m), with indices first increasing sharply then decreasing. The remaining ten mountain ranges show approximately normal distributions with distinct morphological characteristics. Lower-latitude ranges like the Himalayas, Nyainqentanglha, and Karakoram, located in warmer regions with abundant precipitation, show broader dominant altitude ranges. In contrast, the Gangdise, Qiangtang, and Kunlun ranges, dominated by extreme continental glaciers in arid regions, show narrower altitude distributions with tall, narrow curves.

[Figure 5: see original paper]

4 Discussion

The relationship between glacier distribution patterns and topographic factors in the Tibetan Plateau has long been a critical topic in geography and glaciology. This study finds that glaciers exhibit broad suitability for aspect and slope but strong selectivity for RDLS and altitude, with dominant distribution at high RDLS and high altitudes. Geodetector results confirm altitude and RDLS as the primary controlling factors, with their combined effect most significantly influencing spatial heterogeneity—consistent with previous research. However, the explanatory power of individual or combined terrain factors varies markedly among mountain ranges, likely related to their unique regional positions and climatic conditions.

Glacier distribution in the Tibetan Plateau is influenced by multiple meteorological factors, with temperature and precipitation forming the material basis for glacier development. These factors interact with topography to determine glacier formation, development, and retreat. The plateau's glaciers are primarily affected by the southwest monsoon, southeast monsoon, South Asian monsoon, and westerly circulation, with outer windward slopes receiving abundant precipitation favorable for glacier development, while leeward slopes receive less due to mountain blocking. The northern boundary of the Asian summer monsoon climate extends along the eastern Qilian Mountains, dividing the plateau into a westerly-influenced arid region to the north and a monsoon-influenced humid region to the south. Terrain factors show stronger explanatory power for glacier distribution in the arid northern region and weaker power in the humid southern region. The Gangdise-Nyainqentanglha range, serving as the boundary for both the plateau' s climate zones and the -10°C mean temperature in the coldest month, exhibits significant north-south differences in thermal and moisture conditions, with temperature differences showing "jump" characteristics that determine contrasting glacier distribution patterns on either side. These unique climatic features may explain why terrain factors show the weakest explanatory power for glacier distribution in the Gangdise and Nyainqentanglha ranges.

Terrain and climate jointly cause distribution pattern differences among mountain ranges. Most glacier distributions show approximately normal patterns, peaking in specific terrain bands where conditions are most suitable. However, peak heights and dominant distribution ranges vary, creating distinct morphological features. Lower-latitude ranges like the Himalayas, Nyainqentanglha, and Karakoram, with abundant heat and precipitation, support glaciers across broader altitude ranges. In contrast, the Gangdise, Qiangtang, and Kunlun ranges, dominated by extreme continental glaciers in arid regions with limited precipitation, show more concentrated altitude distributions with tall, narrow curves. Marine-type glaciers in the eastern Nyainqentanglha and Hengduan ranges, located in the transition zone between monsoon systems with complex terrain and strong regional differences, also show broad dominant altitude ranges and multi-peak patterns due to abundant precipitation.

While topographic factors clearly indicate glacier distribution patterns, their predictive power may be influenced by temperature, precipitation, wind direction, and location in specific regions. This study only examines glacier area distribution across terrain gradients; future research should investigate glacier volume, thickness, length, and equilibrium line altitude. Additionally, the lack of meteorological observation data limits causal analysis of glacier influences in the Tibetan Plateau. Future studies should couple glacier distribution patterns and spatiotemporal changes across scales, integrating meteorological, topographic, and anthropogenic factors to develop glacier system models for simulating and predicting glacier change trends and quantitatively assessing impacts on global climate and environmental change.

5 Conclusions

Based on Randolph Glacier Inventory data and NASADEM, this study determined the optimal RDLS calculation window for the Tibetan Plateau using mean change-point analysis and analyzed distribution patterns and causes of glaciers across mountain ranges using distribution index and geodetector techniques. The main conclusions are:

(1) Glaciers in the Tibetan Plateau show broad suitability for aspect and slope but strong selectivity for RDLS and altitude, with dominant distribution at high RDLS and high altitudes. Distribution indices increase with rising RDLS and altitude, showing dominant distribution in RDLS class 5 (5.0795–11.5973) and altitude class 5 (5082–8781 m). Glaciers exhibit dominant distribution on north, northeast, east, and northwest aspects, with the highest index on north-facing slopes, followed by northeast-facing slopes. Glaciers show the broadest suitability for slope, with distribution indices concentrated around the standard value in slope class 1 (5.0623°–36.1110°), increasing as slopes steepen.

(2) Terrain significantly influences glacier development, with topographic factors having distinct effects on glacier spatial distribution. Altitude and RDLS are the primary controlling factors, followed by slope and aspect. Interactive detection reveals that terrain factors do not independently influence glacier distribution; any two-factor interaction exceeds single-factor effects, showing dual-factor enhancement and nonlinear amplification without independent or weakening relationships. The combined effect of altitude and RDLS most significantly influences glacier spatial heterogeneity.

(3) Along RDLS gradients, the Himalayas, Karakoram, and Pamir show dominant glacier distribution across more than 10 intervals, with the Himalayas showing the most extensive range. Along altitude gradients, the Himalayas also show the broadest dominant distribution range, with indices increasing sharply then stabilizing with rising altitude. The Karakoram shows a broad dominant range with a sharp increase followed by decrease. The remaining ten mountain ranges show approximately normal distributions

with distinct morphological characteristics.

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