

## Article

# Simulation of the Potential Distribution of the Glacier Based on Maximum Entropy Model in the Tianshan Mountains, China

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**Abstract:** Under the background of global climate change, the variation in the spatial distribution and ice volume of mountain glaciers have a profound influence on regional economic development and ecological security. The development of glaciers is like biological succession; when climate change approaches or exceeds the threshold of suitable conditions for glacier development, it will lead to changes in potential distribution pattern. Therefore, from the perspective of the “biological” characteristics of glaciers, it is a beneficial exploration and attempt in the field of glaciology to explore its potential distribution law with the help of the niche model. The maximum entropy model (MaxEnt) can explain the environmental conditions suitable for the survival of things by analyzing the mathematical characteristics and distribution laws of samples in space. According to glacier samples and the geographical environment data screened by correlation analysis and iterative calculation, the potential distribution pattern of Tianshan glaciers in China in reference years (1970–2000) was simulated by MaxEnt. This paper describes the contribution of geographical environmental factors to distribution of glaciers in Tianshan Mountains, quantifies the threshold range of factors affecting the suitable habitat of glaciers, and predicts the area variation and distribution pattern of glaciers under different climate scenarios (SSP1-2.6, SSP5-8.5) in the future (2040–2060, 2080–2100). The results show that the MaxEnt model has good adaptability to simulate the distribution of glaciers. The spatial heterogeneity of potential distribution of glaciers is caused by the spatio-temporal differences of hydrothermal combination and topographic conditions. Among the environmental variables, precipitation during the wettest month, altitude, annual mean temperature, and temperature seasonality have more significant effects on the potential distribution of glaciers. There is significant spatial heterogeneity in the potential distribution of glaciers in different watersheds, altitudes, and aspects. From the forecast results of glacier in various climatic scenarios in the future, about 18.16–27.62% of the total reference year glacier area are in an alternating change of melting and accumulation, among which few glaciers are increasing, but this has not changed the overall retreat trend of glaciers in the study area. Under the low emission scenario, the glacier area of the Tianshan Mountains in China decreased by 18.18% and 23.73% respectively in the middle and end of the 21st century compared with the reference years and decreased by 20.04% and 27.63%, respectively, under the high emission scenario, which showed that the extent of glacier retreat is more intense under the high emission scenario. Our study offers momentous theoretical value and practical significance for enriching and expanding the theories and analytical methods of the glacier change.

**Keywords:** mountain glacier; the MaxEnt model; potential distribution; climate scenario; Tianshan Mountains of China



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## 1. Introduction

Against a background of global climate change, the response mechanism of the glacier fluctuation to geographical environmental factors, such as climate and topography, is one of the research hotspots in the cryosphere [1]. The regulation of river runoff by glacier changes in the future is also the focus of regional sustainable development.

Alpine glaciers widely distributed in mid-low latitudes are not only extremely sensitive to climate change, but they are also affected by the combination of hydrothermal and topographical conditions [2]. Just as the distribution, development, and succession of plants and animals are highly dependent on their external abiotic environment, the spatial and temporal distribution will change as the habitat changes. When climate change approaches or exceeds the threshold of suitable for glacier distribution, it will lead to changes in potential distribution patterns, for example, the glacier terminus fluctuations are a good reflection of its adaptation to climate change [3]. From this perspective, glaciers also have certain “biological” characteristics.

Previous studies on the glacier area change and its spatial and temporal differentiation were mainly based on topographic maps, aerial photographs, satellites, and remote sensing images. The glacier area was obtained by field measurement, remote sensing interpretation, geospatial analysis, model simulation, and other technical means [4]. Among them, glacier information obtained from topographic maps, aerial photographs, and field measurements has high accuracy, but there are great limitations in obtaining continuous glaciers change information at large spatial-temporal scales [5]. Although remote sensing data has the advantages of extensive range and multiple time series and has been widely used in monitoring glacier changes. However, due to the variable weather conditions, debris-covered and mountain shadows, the commonly used optical remote sensing to extract the glacier boundary is subject to large uncertainties. In fact, the surface debris-covered at the end of glacier not only caused great interference to the glacier boundary extraction and thickness monitoring, but also seriously underestimated the overall retreat and volume loss of the glacier, and even produced the misjudgment of “the glacier area was relatively stable”. This phenomenon was found in the Tomur Glacier in China after field investigations [6–8]. Some researchers believed that there was a large number of glaciers covered with debris. Due to the lack of field-observed data, the spatial distribution and influence of the glacial debris-coverage are still unclear [9,10]. Thus, the glacier area obtained by remote sensing interpretation may not reflect the actual distribution accurately and objectively and may be greatly underestimated or uncertain. Therefore, mathematical models provide a good alternative for exploring the response mechanism of the glacier changes to climate, but in almost all such studies, they still have certain limitations. For instance, the statistical models such as partial least squares are used to analyze glacier changes and their relationship with influencing factors. Because it ignores the multiple correlations among the factors, the simulation accuracy of the glacier change needs to be further improved [11]. The glacier dynamic model is used to simulate and predict the glacier response process under the background of climate change. Due to the higher requirements of physics model for the glacier observation parameters, it is only suitable for a single glacier with complete observation data [12]. The glacier changes will inevitably affect global and regional ecological environment and eco-hydrological processes. In addition, under future climate scenarios, the possibility of changes in the area and pattern of glaciers has aroused widespread concern in the academic and socio-economic fields. At present, most scholars predict glacier changes at the watershed or regional scale based on the coupled model of the climate-glacier interaction response process and glacier system model [13–16]. However, due to differences in climate scenario assumptions and model principles, there are some differences and divergences in many prediction results. Applying the niche model theory to the glacier research can help us understand glaciers from a more comprehensive, objective, and novel perspective.

In the field of glaciology, altitude, slope, temperature, and precipitation in different seasons have created suitable “habitat” conditions for the formation and development

of glaciers. The unique living conditions and distribution characteristics of glaciers in large-scale environment space are explained by analyzing the mathematical characteristics and distribution laws of sample data in geographical environment space [17,18]. The maximum entropy model (MaxEnt) remains an active area of research, and its applications in diverse areas are still being explored at the annual conference [19]. It is more inclined to simulate and explain the laws of natural phenomena, which are no longer limited to the potential distribution of species, and has attracted attention in abiotic fields, such as the interaction between population and social environment [20,21], the planning of protected areas [22], the optimization of settlement pattern [23], the assessment of natural disasters such as flood and landslide susceptibility [24], and the prediction of suitable areas for potential distribution of wetlands [25]. It has many advantages over other models, including dealing with complex interactions between variables, low sensitivity to small samples, among others [26]. Therefore, this paper tries to introduce the niche theory into the field of glaciology, and explore the current and future distribution of glaciers, and analyze the various possibilities of the glacier changes in different climate scenarios [27]. This new view of the glacier "biology" has important theoretical value and practical significance for enriching and expanding glacier change theory and analysis methods.

As the source of runoff from many rivers in the arid region of Central Asia, the glacier in Tianshan Mountains play an irreplaceable role. In the past half century, the alpine glaciers have been retreating, which has had a great impact on the hydrological characteristics, water resources, ecological environment, and socio-economic development in the region [28]. In this paper, we combined the prediction of geographic distribution with the research of Tianshan glaciers and used the MaxEnt to simulate the potential distribution of glaciers by referring to the relevant theories, technologies and methods of the niche model. The research will first help to explore which environmental factors affect the distribution of glaciers and establish their contribution. Next, we clarify the threshold range of the influencing factors of glacier suitable habitat, and further predict the possible changes of spatial distribution pattern and scale of glaciers in future climate scenarios.

## 2. Study Area

The Tianshan Mountains, also known as the "Water Tower of Central Asian", is located in the hinterland of Eurasia. It is one of the most developed mountains with modern glaciers in the world and one of the most sensitive areas for global climate change [29]. The part of it in China, with coordinates of 39.34°–45.43° N and 73.8°–96.37° E, stretches 1700 km from east to west, and spans the whole territory of Xinjiang, covering an area of  $5.7 \times 10^5$  km<sup>2</sup> [30–32]. It is composed of a series of parallel mountains running east to west and surrounded by the Taklimakan and Gurbantunggut Deserts in north and south [33] (Figure 1). Influenced by westerly airflow and Arctic Ocean air mass, the precipitation in Tianshan Mountains with significant spatial difference decreases from west to east, and the northern slope is more than the southern slope [30]. On the basis of the Chinese Glacier Inventory, the glaciers in Tianshan District of China have different morphological types, and most of them are small-area glaciers, which are distributed in the Tarim River System, the Junggar River System, the Turpan-Hami River System, and the Yili River System [31].

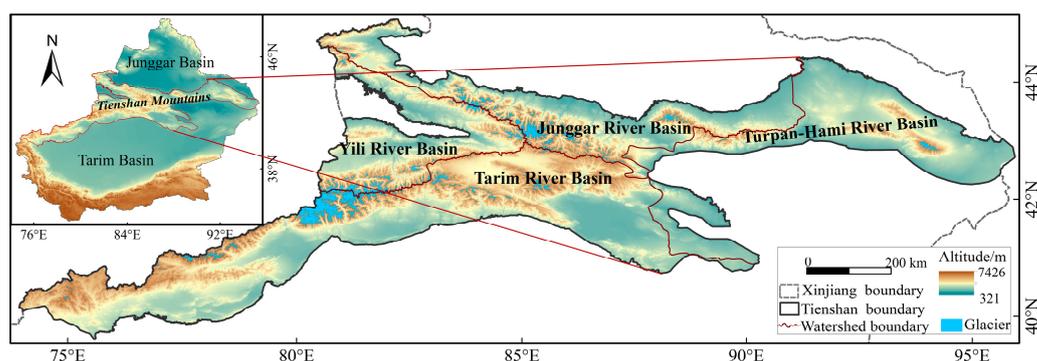


Figure 1. Location of the study area in China.

### 3. Data and Methods

#### 3.1. Data Description

The data includes mainly the glacier vector data and geographic environment data such as climate and topography (Table 1). The glacier vector data was taken from the Second Chinese Glacier Inventory data (2006–2010), which was used to randomly extract the geographical coordinates of points as glacier sample data and test simulation accuracy of the model. The climate data includes such variables as temperature factors (Bio01–Bio11), precipitation factors (Bio12–Bio19), solar radiation, wind speed, and land surface reflectance, which are closely related to the distribution and development of glaciers at historical (1970–2000) [34] and future (2041–2060 and 2081–2100) periods. The DEM was used to extract topographic factors and divide the elevation zone of the glaciers' distribution.

Table 1. Data sources.

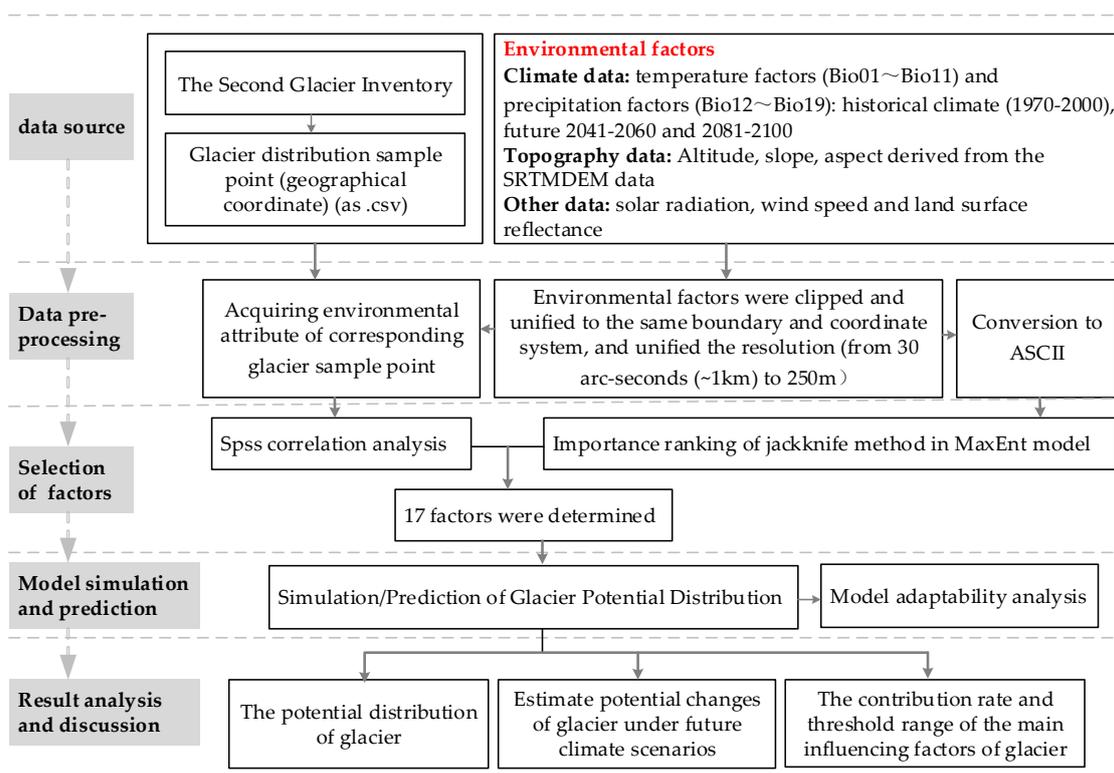
Category	Time	Resolution	Official Website (Accessed Date 27 May 2021)
Second Glacier Inventory Dataset	2009	30 m	National Cryosphere Desert Data Center ( <a href="https://www.crensed.ac.cn/portal/">https://www.crensed.ac.cn/portal/</a> )
Bio01–Bio19 solar radiation wind speed	1970–2000 (Reference years)	30"	Worldclim Global Climate Data ( <a href="http://www.worldclim.org">http://www.worldclim.org</a> )
surface reflectance	2009	250 m	Geospatial Data Cloud ( <a href="http://www.gscloud.cn/">http://www.gscloud.cn/</a> )
ssp126bc ssp585bc	2041–2060	2.5'	Worldclim Global Climate Data ( <a href="http://www.worldclim.org">http://www.worldclim.org</a> )
ssp126bc ssp585bc	2081–2100		
DEM	—	90 m	Geospatial Data Cloud ( <a href="http://www.gscloud.cn/">http://www.gscloud.cn/</a> )

The climate data in the study came from 1970 to 2000, and the glacier distribution point data came from the Second Chinese Glacier Inventory data (remote sensing image data interpreted from 2006 to 2010). Due to the limitation of data, we could not obtain the data of the same time, but the data of the Second Chinese Glacier Inventory could better reflect the current glacier distribution, and the time of obtaining the image was also relatively close to the time period of climate data from 1970 to 2000. They could well reflect and simulate the impact of climate change in the past 30 years on the current glaciers. Finally, taking 1970–2000 as reference years, this paper analyzes the glacier distribution changes under future climate scenarios.

#### 3.2. Research Method

MaxEnt is derived from the maximum entropy theory, which is an existing machine learning distribution algorithm. It is commonly used to predict niches and probability

distribution by identifying nonlinear relationships between environmental variables and known locations [35]. It is an appropriate tool for mapping glacier potential distribution in the study area under various climate change scenarios. The workflow is shown in Figure 2. Briefly, the data were first collected and preprocessed. Next, the environmental factors were analyzed and screened, and then the MaxEnt model was run by adjusting the parameters to simulate the current and predicted future glaciers distribution. Finally, the resulting data were comprehensively evaluated.



**Figure 2.** Workflow of the MaxEnt model for the glacier potential distribution.

### 3.2.1. Collection of Glacier Sampling Points

Because there were few observed values in the glacier distribution area, there were great limitations in collecting data directly through field investigation. Using GIS software to obtain glacier sample points from the glacier distribution area, we tried to find the environmental characteristics such as climate and topography in this area and establish the connection between environmental factors and glaciers with these points as a link, which provided basic driving data for model operation. Random points were generated by the creation points function in the tool of ArcGIS data management tool. Then, about 2500 glacier sample points were extracted by superimposing and intersecting with the Second Glacier Inventory data, to ensure that all these points covered most regions where the glacier was known to exist. Finally, glacier sampling points were identified, and their geographic locations (latitude and longitude) were organized into “.csv” format files. Final sampling point distribution across altitudes/annual precipitation/mean annual air temperature is shown in Supplementary File S1.

### 3.2.2. Environmental Parameters

The distribution and change of glacier were believed to be strongly influenced by many factors [36]. Previous studies mostly analyzed the response of glaciers to climate change based on the hydrothermal combination and topographical conditions [37,38]. However, few researchers have integrated many geographical environmental factors to

explore the compound effects on the glacier changes [39]. Therefore, higher-dimensional and finer-grained data were needed to support the analysis of spatio-temporal difference mechanism of the glacier changes. In this study, besides the conventional factors such as temperature, precipitation, altitude, slope, aspect, etc., the extreme or restrictive climatic factors that affected the development and evolution of the glacier were also fully considered (precipitation and temperature of the coldest and warmest month, precipitation of the wettest and driest month, etc.), to better simulate and analyze the suitable habitat conditions of glaciers (Table 2).

**Table 2.** Environmental variables used in the study and their contribution rate in simulating the potential distribution of glaciers.

Abbreviation	Description	Contribution (%)	Cumulative Contribution (%)
Bio13	Precipitation of Wettest Month (mm)	30.5	30.5
Alt	Altitude (m)	24	54.5
Bio1	Annual Mean Temperature (°C)	10.2	64.7
Bio4	Temperature Seasonality (standard deviation × 100) (C of V)	6.1	70.8
Bio7	Temperature Annual Range (Bio5–Bio6) (°C)	6	76.8
Sur	surface reflectance	5	81.8
Bio6	Min Temperature of Coldest Month (°C)	4.8	86.6
Asp	Aspect (°)	3.6	90.2
Bio12	Annual Precipitation (mm)	2.6	92.8
Bio2	Mean Diurnal Range (Mean of monthly (max temp–min temp)) (°C)	2.2	95
SR3	Solar radiation in March ( $\text{kJ m}^{-2} \text{day}^{-1}$ )	1.3	96.3
SR5	Solar radiation in May ( $\text{kJ m}^{-2} \text{day}^{-1}$ )	1.1	97.4
Wind01	wind speed in January ( $\text{m s}^{-1}$ )	1.1	98.5
SR10	Solar radiation in October ( $\text{kJ m}^{-2} \text{day}^{-1}$ )	1	99.5
Wind10	Wind speed in October ( $\text{m s}^{-1}$ )	0.2	99.7
Bio14	Precipitation of Driest Month (mm)	0.2	99.9
Slp	Slope (°)	0.1	100

The original data were screened and preprocessed in this paper to avoid the over-fitting of the model caused by multi-collinearity among environmental variables, so that the environmental factors involved in modeling were more representative [40]. First, the attribute characteristics of 43 environment variables were extracted, and the factors with higher correlation coefficients were removed by using SPSS correlation analysis (Supplementary File S2 for details). For example, the mean temperature of warmest quarter was highly correlated with the annual mean temperature, and the precipitation of driest quarter and coldest quarter were highly correlated with the precipitation of driest month, and the wind speed between February, April, June, August, September, and December were highly correlated with other months, the solar radiation in April, June–September, November, and December were strongly correlated with other months,

so they were removed. Second, the Jackknife function of the MaxEnt model was used to obtain as much information as possible about the potential distribution of glaciers from limited environmental data, which could effectively reduce the estimation bias, and then quantitatively judged the contribution of each various environmental to the simulation of potential distribution of glaciers [20,40]. In this paper, it was also used to test the response degree of the glacier distribution changes to environmental factors, obtained the dominant environmental variables that affect the glacier distribution and eliminated the factors that have zero importance to the potential distribution of glaciers, such as isotherm, mean temperature of the wettest quarter, max temperature of the warmest month, solar radiation in January, February, and June, and wind speed in odd months. According to the method of SPSS and Jackknife, the final 17 factors that affecting the suitable habitat of the glacier were selected (Table 2). According to the Jackknife estimation module of the model, the cumulative contribution rate of the top ten environmental factors reached 95%, which showed that these were the main environmental factors affecting the potential distribution of glaciers. In addition, bilinear interpolation was used for resampling, and the resolution was resampled from 30 arc-seconds (~1 km) to 250 m, to unify the resolution of various environmental factors and improve the accuracy of describing the suitable habitat distribution of glaciers. Finally, all layers were clipped and unified to the same boundary and coordinate system, converted into ASCII format.

The future variables were derived from the new climate scenarios proposed in the Sixth International Coupling Model Comparison Program (CMIP6), namely Shared Economic Paths (SSPs), which had a higher starting point for prediction than RCPs and can provide More diverse air pollution emission scenarios [41]. Among them, SSP1-2.6 and SSP5-8.5 described the lowest-emission sustainable development scenario and the highest-emission conventional development scenario respectively, which were selected to drive the optimized MaxEnt model to predict the changes of glaciers in the future and provided more reasonable evaluation conditions for the study of the glacier future trends.

### 3.2.3. Glacier Distribution Model Processing

The maximum entropy model is a machine learning method that estimates the distribution of species through the possible distribution of maximum entropy [42]. The algorithm calculates the most probable potential geographic distribution of species, based on the relationship between the geographical data and the known distribution of the target species [19]. The main working principle is [43,44], given the sample  $x$  and the factors  $f_1, f_2 \dots$ , carry out iterative calculation for many times. Every iterative calculation will increase the probability of the sample  $x$ , and the gain starts from 0 increases with the increase of  $P$  value of the sampled position, until the model converges to  $c_1, c_2 \dots$ , and we get the optimal  $P$  value.

$$P(x) = \exp(c_1 f_1(x) + c_2 f_2(x) + c_3 f_3(x) \dots) / Z \quad (1)$$

In Equation (1),  $P(x)$  is the optimal distribution,  $x$  is a sample,  $c_1, c_2 \dots$  are constants,  $f_1(x), f_2(x) \dots$  are influence factors,  $Z$  is a proportional constant, ensure that  $P$  increases to 1 on all grids.

The potential distribution of glaciers was simulated with reference to the simulation ideas of other ecological species. That is to say, the geographical coordinates of sample points and corresponding environmental factors were imported into the model to simulate the maximum possibility of potential distribution of glaciers. In order to be better applied to the glacier research, it was necessary to calibrate the model parameters to improve the reliability and accuracy of the simulation results. The feature type combination (FC) was the key parameter setting of the MaxEnt model. Researchers often used five default parameters of feature types (linear, quadratic, product, threshold, and hinge features) [17]. After many attempts in this study, it was found that the prediction level of the default value can be achieved by selecting the combination of linear and quadratic features, and the algorithm was simple and fast, which was more advantageous for big data processing. In this paper, the maximum number of background points was set to 15,000 and the regulation

frequency multiplier was 1 to ensure the model has well regulation of the response curve for each factor, while the other values were kept at their default levels [45]. To reduce the potential effects of spatial autocorrelation in the model building, we ran the model 10 times, cross validating the data with a random 25% of the occurrence records, and 75% of the data were selected as training samples.

#### 3.2.4. Model Adaptability and Determination of Glacier Potential Distribution Area

The MaxEnt model was considered as one of the models with the best predictive ability and accuracy among many models for studying the potential distribution of species [26]. The accuracy of the model prediction was quantified by calculating the area under the Receiver Operating Characteristic (ROC) curve (AUC) [46]. However, there is no precedent for simulating and predicting the potential distribution of glaciers based on this model. Thus, we referred to the evaluation standards AUC values in other fields to further verify its adaptability for the glacier research. AUC values below 0.7 were considered as poor, values between 0.7 and 0.9 were moderate, and values above 0.9 were considered as high [47]. In this study, the mean (AUC value for the current climate) was particularly high at 0.916 for the replicate runs, which showed that the results of model performance were acceptable for predicting the potential distribution of glaciers. According to the suitability analysis of MaxEnt model in other fields, such as the optimization of settlement pattern [23] and the risk assessment of mountain torrents and landslides [24], good simulation and prediction results were obtained. Thus, it was very feasible and adaptable to use the MaxEnt model in this study.

Finally, with the help of ArcGIS, the simulation results were visualized through ASCII to TIFF format conversion, reclassification and vector grid conversion, and the potential distribution probability (0–1) of Tianshan glaciers in China was obtained. Since the natural breakpoint method used the inflection point of the frequency curve of the fitness probability distribution as the grading boundary value [25], based on this method, the interval higher than the default threshold of the model (>0.54) was selected as the potential suitable distribution range of glaciers.

## 4. Results

### 4.1. Potential Distribution of Tianshan Glaciers in China under Current Climate Environment

#### 4.1.1. Overall Characteristics of the Glacier Potential Distribution

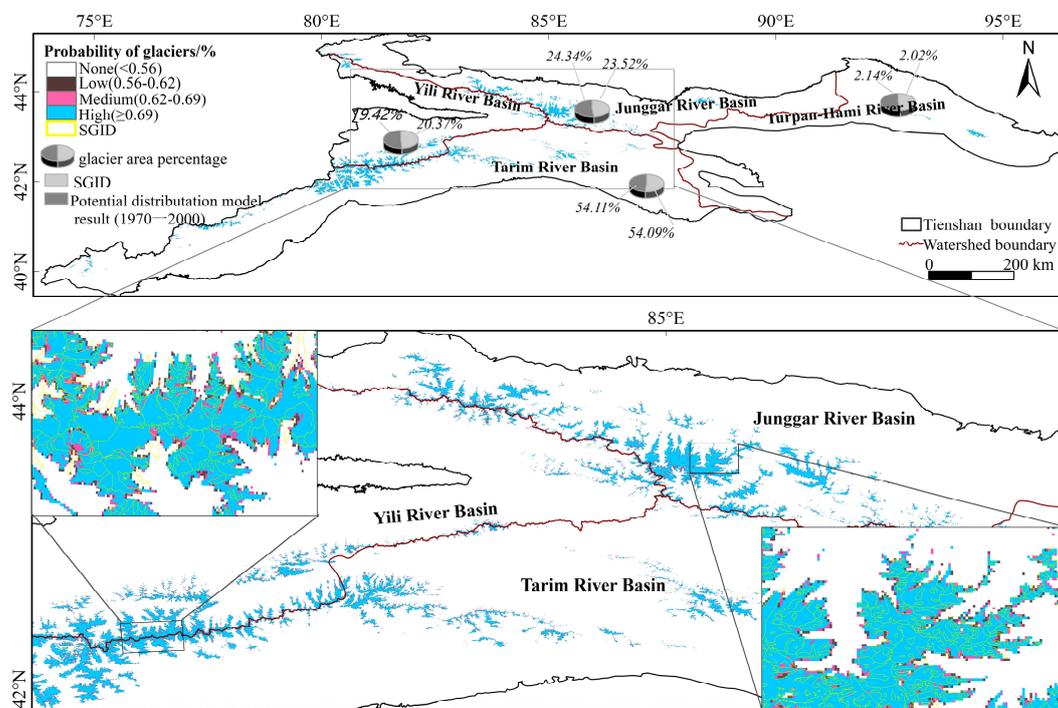
According to the model simulation results, the habitat suitability predictions were reclassified into three categories, including low (54–62%), medium (62–69%), and high (>69%), and the values below 54% were considered as non-suitable habitat (Table 3). The simulation showed that the potential distribution area of Tianshan glaciers in reference years (1970–2000) was 7886.84 km<sup>2</sup>, accounting for 2.41% of the whole study area, with an average altitude of about 4198 m. The low and medium suitable glaciers accounted for 1.77% of the study area, scattered around the high suitable area, with an average elevation of about 3946 m. According to the statistics of the Second Glacier Inventory, the glacier area of Tianshan was about 7246.60 km<sup>2</sup>, the glacier coverage rate was 2.22%, and the average altitude was about 4202.91 m. Compared with the Second Glacier Inventory data, this study found that potential distribution of highly suitable locations of glaciers was not only good in agreement in the glacier coverage, but also had a similar distribution pattern in altitude, which could well reflect the distribution of glaciers. However, the glacier fragmentation in the low and medium suitable areas was serious and quite different from the glacier catalogue data. In addition, related studies have shown that the MaxEnt model can overestimate the prediction results [19]. Therefore, in the follow-up study of this article, only the potential distribution of glaciers in highly suitable regions were discussed to improve the accuracy of the glacier simulation results.

**Table 3.** The potential suitable distribution of glaciers in reference years (1970–2000).

Glacier Suitability	Potential Distribution Area /km <sup>2</sup>	Coverage Rate /%	Average Altitude /m
Non suitable	313,105.65	95.5	—
Low suitable	3019.11	0.92	3907.18
Medium suitable	2801.68	0.85	3984.5
High suitable	7886.84	2.41	4198.74
Second glacier inventory	7246.60	2.22	4202.91

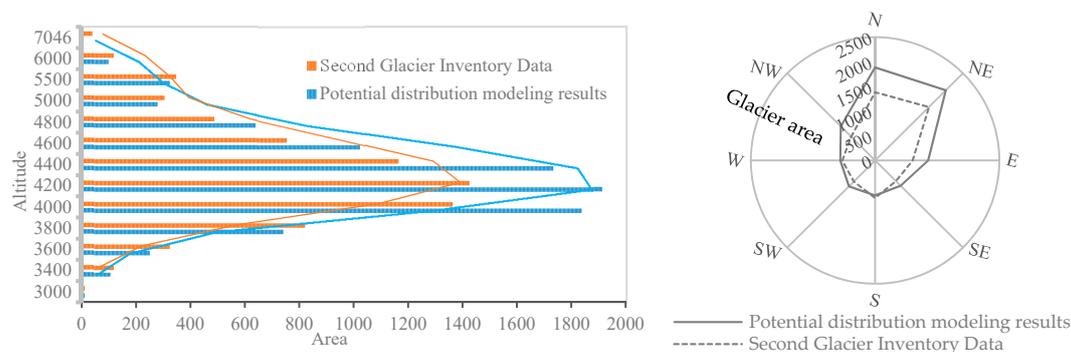
4.1.2. Spatial Characteristics of the Glacier Potential Distribution

Due to the uneven distribution of environmental variables such as topographical fluctuations and hydrothermal conditions, there are significant regional differences in potential distribution of glaciers. The scale of glaciers in different watersheds of the study area was different, the highly suitable glacier areas of Tarim River, Junggar River, Yili River, and Turpan-Hami River were 4267.53 km<sup>2</sup>, 1919.36 km<sup>2</sup>, 1531.34 km<sup>2</sup>, and 168.61 km<sup>2</sup>, respectively, accounted for 2.98%, 3.12%, 2.08%, and 0.36% of the watershed area, respectively. Among them, the high suitable areas located in the Tarim River in the south and Junggar River in the north accounted for 54.11% and 24.34% of the total glacier area, respectively. The areas of highly suitable of Tu-Ha River in the east and Yili River in the west accounted for 2.14% and 19.42% of the total glacier area, respectively (Figure 3). In the last 60 years, the annual precipitation of Tianshan Mountains in China has been characterized by the center of low precipitation in eastern mountainous area represented by the Tu-Ha Basin and the center of high precipitation represented by Yili River Valley [48]. That is, the centers of “dry heat” and “warm humidity” appeared in the east and northwest of mountainous areas. It can be inferred that the huge difference of the glacier area in the east-west direction is caused by the difference of precipitation and heat.



**Figure 3.** The potential distribution of glaciers can be showed more clearly by local enlargement in reference years (1970–2000). SGID represents the Second Glacier Inventory of china. Glacier area percentage in the figure represents the ratio of glaciers in high suitable areas of each River Basin to the whole study regions’ area.

As far as the potential distribution of glaciers at different altitudes in Tianshan Mountains, China, the potential distribution area of glaciers was approximately normal distribution with altitude (Figure 4), and the peak of elevation appeared near 4200 m. The mean elevation of the potential distribution of glaciers in the southern Tianshan Mountains was generally about 151–820 m higher than that in the northern, which was consistent with the conclusion that snowline altitude on the north slope of the Tianshan Mountains was lower than the south slope [5]. Among them, the potential distribution area of glaciers at an altitude of 3800–4800 m accounted for about 88% of the total area, which was the most concentrated area of glaciers development. This was highly consistent with the statistical distribution trend in the second glacier catalog data. Combined with the altitude classification standards of the China Digital Geomorphology Classification System, the potential glacier area was 364.46 km<sup>2</sup> in median altitude (1000–3500 m), 8148.23 km<sup>2</sup> in high altitude (3500–5000 m) and 424.11 km<sup>2</sup> in extremely high altitude ( $\geq 5000$  m). It can be seen that about 90% of glaciers were mainly distributed in high altitude areas, which was consistent with the results obtained on the spatial distribution pattern of glaciers in China [49]. The potential distribution of the glacier area showed obvious vertical zonality, which might be caused by the significant differences in the environmental factors at different altitudes [50,51].



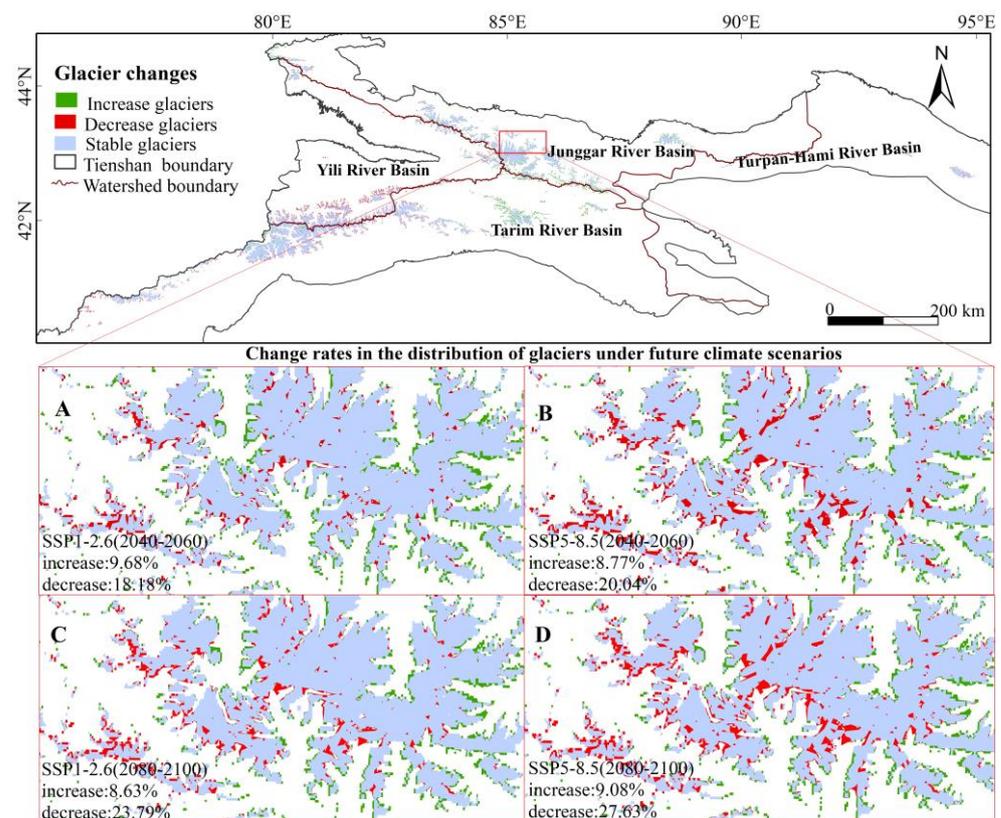
**Figure 4.** Hypsography and Orientational characteristics of the glacier distribution in the Tianshan Mountains, China.

In terms of the potential distribution of glaciers in various directions (Figure 4), The glacier area in the northeast of Tianshan Mountains in China was the largest, followed by the north, and the west and south were smaller, accounting for about 16% of the total glacier area. This distribution was largely related to the fact that the south slope belongs to the sunny slope and gets more solar radiation while the north slope had weaker solar radiation [48]. In addition, due to the Tianshan Mountains are mostly east-west, a natural barrier which makes the south slope of the mountains a leeward slope and blocks the ocean water vapor from flowing southward. This makes the north slope have a lower temperature and more precipitation than the south, which is more conducive to the accumulation and development of glaciers on the north slope [45].

#### 4.2. Features of the Glacier Shifts in Tianshan Mountains of China under Future Climate Scenarios

With the background of global warming climate, the trend of the glacier retreat is severe, and many smaller glaciers are facing the risk of disappearing, which will increase the difficulty of water resources management and allocation, and the risk of increasing frequency of natural disasters such as the glacier floods and mudslides. Therefore, it is necessary to predict the trend of the glacier shifts in the future. In the future climate scenario, although SSPs assumes an “aggressive” carbon-limiting policy, the global total emissions will be negative by 2080, but the temperature in the Tianshan area has already shown an upward trend, and the glaciers are generally shrinking. As shown in Figure 5, under the low emission scenario of SSP1-2.6, compared with the base year, the glacier area will be decreased by 18.18% and 23.79%, respectively, in the middle and the end of the 21st century. Under the high emission scenario of SSP5-8.5, compared with the

base year, the glacier area will be decreased by 20.04% and 27.63% in the middle and the end of the 21st century, respectively, which shows that the glacier retreat is more severe under the high emission scenario. Through the statistical prediction results, the area of glaciers in most regions is in a relatively stable state and about 18.16–27.62% of the total glacier area in the reference years is in an alternating change of melting/accumulation. The glacier area in a few regions will increase, but after the expansion of advancing glacier area and the reduction of retreating glacier offset each other, especially in the case of high emission, the whole glacier area is still shrinking. As a huge reservoir, the simulation and estimation of glaciers mostly depend on the understanding of glacier change process and the establishment of models [12]. Sun et al. predicted that the glacier retreat rate will be 15%, 20%, and 25%, respectively, under the three emission scenarios of low, medium and high in the middle of the 21st century [52]. Shi et al. comprehensively considered the trend of the glacier reduction in China in the 21st century, it was estimated that the glacier area will be reduced by 28% in 2070, and 30% to 67% by 2100 [53]. Xie et al. hypothesized that the glacier area in China will be reduced by 14% and 40%, respectively, by the end of the 21st century when the heating rate is  $0.01 \text{ K}\cdot\text{a}^{-1}$  and  $0.03 \text{ K}\cdot\text{a}^{-1}$  [54]. This paper used the niche model to find that the glacier area would be reduced by 18–24% in low emission scenario and 20–28% in high emission scenario, which is conservative compared with the prediction results of predecessors. The reason may be that most previous related studies only considered the influence of temperature and precipitation on the future changes of glaciers, while more geographical environmental factors are introduced into the MaxEnt model, which can more objectively predict the future shifts of the glacier area.

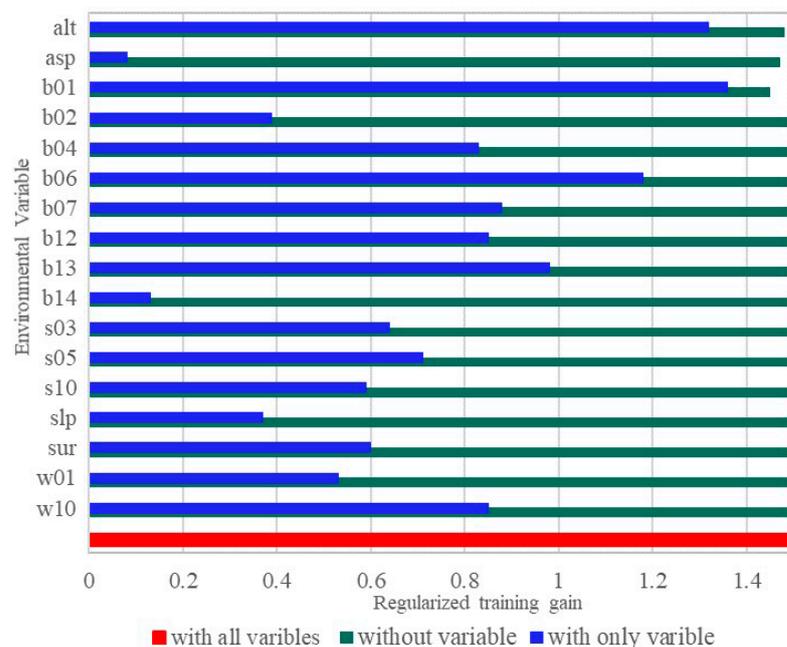


**Figure 5.** Changes in the distribution of glaciers under future climate scenarios. Compared with the reference year (1970–2000), the potential distribution of glaciers in SSP1-2.6 (A,C) and SSP5-8.5 (B,D) scenarios in the middle and late of the 21st century.

## 5. Discussion

### 5.1. Importance of Environmental Variables to Potential Distribution of Mountain Glaciers

Temperature and precipitation provide the material basis for the formation and development of glaciers, while slope and altitude provide the topographic basis for material accumulation for its development [55]. The habitats of glaciers are composed of many factors. In the past, researchers mostly analyzed the effects of temperature and precipitation on the distribution patterns of glaciers from a macro level, but according to the existing data, it is difficult to explain the spatial differentiation law in glaciers change based on these two factors alone [56]. Therefore, it is recommended to analyze the influence of geographical environment factors on the glacier distribution from more detailed granularity. Individual Jackknife tests for the glacier suitable habitat also highlighted the importance of environmental variables (Figure 6). When a factor was used in isolation or omitted for simulation, the annual average temperature, altitude and aspect had the most useful information, which had a great influence on the simulation results. When predicting the glacier distribution in the future climate scenario, the selection of the prediction factor category is the same as that of simulating the potential distribution. It is concluded that in the future climate situation, the most significant factors affecting glaciers are still temperature and precipitation, followed by altitude, other factors also have different degrees of influence on them. In summary, we found that all environmental factors carry very important information, which is the key factor affecting the potential distribution of glaciers and can better reflect and characterize the survival characteristics of glaciers.



**Figure 6.** Results of the Jackknife test evaluating the importance for the environmental variables.

The spatio-temporal differences of environmental factors lead to the spatio-temporal heterogeneity of the potential distribution pattern of glaciers. The key environmental factors that affect the suitable habitat of glaciers obtained by MaxEnt are consistent with previous research conclusions. For example, some scholar thought that the combination of increasing precipitation and decreasing average temperature in summer was most beneficial to the glacier development [11,57]. Wang et al. pointed out that precipitation increased slowly in the dry season and significantly in the wet season, which was a very important source of the glacier accumulation and the main feature of the continental accumulated glaciers in summer [56]. In addition, glaciers had increased abnormally in some areas, which was closely related to the contribution of precipitation in the wettest month. The reason might be that the increase of solid precipitation on the surface of

glaciers could improve the reflectivity and inhibit the melting of glaciers. The research by Jiang et al [58]. found that low temperature was the main factor affecting the glacier development in areas with less precipitation, which was consistent with the conclusion of this paper that min temperature of coldest month will obviously affect the distribution of glaciers. Liu et al. believed that altitude, slope, solar radiation and other geographical environmental factors also played a decisive role in the distribution and evolution of glaciers [55]. In addition, a large number of studies have also shown that solar radiation, surface reflectivity, and aspect affected the heat received by the glacier, and played an important role in the formation and development of glaciers. It can be seen that the niche model not only has high reliability in simulating the potential distribution of glaciers, but can also comprehensively analyze the impact of environmental factors on the glacier changes from the perspective of multi-granularity.

### *5.2. Threshold Range of Environmental Factors Affecting Potential Distribution of Glaciers*

The glacier changes are affected by many factors and the response mechanism between the glacier changes and geographical environment is complex [36]. The quantitative expression of the threshold range of geographic environmental factors that affect the suitable distribution of glaciers can help us to understand the process and mechanism of the glacier development and evolution. It also provides a reference for the protection of glaciers and the utilization of water resources. Therefore, it is necessary to discuss the ecological scope of various geographical environments that affect the potential distribution of Tianshan glaciers.

According to the change amplitude curve of the main geographical environmental factors in reference years (Figure 7), the threshold range of each factor to the suitable glacier habitat were analyzed. The research results showed that there was not a simple linear relationship between geographical environment factors and the glacier accumulation. The increase in the precipitation of wettest month was conducive to the accumulation of glaciers. In particular, the distribution probability of glaciers increased obviously when the rainfall was between 25 mm and 110 mm, but did not increase continuously when the precipitation exceeded 110 mm. It may be that rain promotes glacier melt and snow feeds the glaciers in their accumulation zone. Moreover, most of the precipitation falling into the glacier area is solid, which provides the basis for the development of glaciers. The little precipitation and the evaporation/sublimation effect were unfavorable to the development of the glacier [59]. With an increase in altitude, the potential distribution probability of glaciers increased, while extremely high and extremely low altitudes were not conducive to the development of glaciers. The reason is that the high surface temperature at extremely low altitude and the steep terrain at very high altitude, coupled with the wind force at the top of the mountain are affect the distribution and long-term existence of glaciers. Among them, an altitude of 3000–4500 m was the area where the potential distribution probability of glaciers increased rapidly and the best terrain area for the glacier development, which was consistent with the conclusions drawn by many researchers such as Xing et al. [31]. Glacier accumulation leads to the increase of surface reflectivity, which in turn reduces the melting of glaciers. However, the surface reflectance not only refers to the reflectance of glacier surface, but also refers to the surface reflectance of the whole mountain area, that is, the surface reflectance of glacier distribution area and its surrounding areas. Because the edge of glacier is mostly bare rock, when the surface reflectance is smaller, it indicates that the bare rocks area absorbs more heat, which will intensify the melting of glacier periphery and make the glacier area smaller [60]. In addition, the darkening of surface glacier caused by the deposition of the Light absorbing impurities can reduce its albedo and further enhance its melting [61]. In this paper, the probability of glacier potential distribution increased with the increase of surface reflectance between 0 and 0.75, and then the speed of glacier accumulation slowed down between 0.75 and 1. The potential distribution probability of glaciers was the lowest when the slope faces south, while the north direction was beneficial to the development of glaciers. This phenomenon may

be attributed to the fact that the southern slope of the Tianshan Mountains is a sunny slope and gets more heat, which leads to a high rate of the glacier ablation. There was a negative correlation between the increase of solar intensity and the glacier accumulation. The potential distribution probability of glaciers continues to decrease when the solar radiation intensity was greater than  $20,100 \text{ kJ m}^{-2} \text{ day}^{-1}$ , which was consistent with the view of Zhang et al. [9], that is, the stronger the solar radiation received by the glacier surface, the weaker the glacier development and accumulation capacity. Through the analysis of the response law of glaciers to the ecological range of various geographical environmental factors, it was shown that the distribution and accumulation of glaciers are not only affected by temperature and precipitation, but also by other factors.

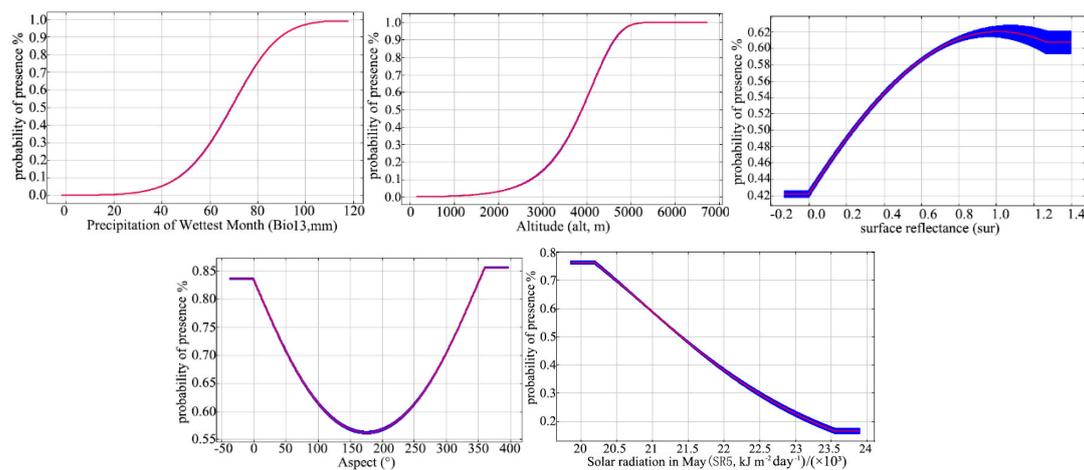


Figure 7. Response curves of geographical environment factors in the glacier suitable habitat.

## 6. Conclusions

In order to explore the response of glaciers to climate change, this paper used MaxEnt model to predict the potential distribution of glaciers under current and future climate conditions. According to the AUC values, our results indicated a good performance of the MaxEnt model and a high level of accuracy for the potential distribution of mountain glaciers. The spatial heterogeneity of potential distribution of glaciers is caused by the spatio-temporal differences of the hydrothermal combination and topographic conditions. However, in addition to temperature and precipitation variables, other factors including precipitation of wettest month, altitude and temperature seasonality, etc., are also the key to the potential distribution of glaciers. By analyzing the suitability grade of potential distribution of glaciers, it is found that the proportion of highly suitable glacier area is 2.72%, which fits well with the results of the Second Glacier Inventory. The potential distribution differences in different watersheds are very significant, among which the proportion of Tarim River area accounts for the highest, followed by Junggar and Yili River area, while the Turpan-Hami area is the least. In future climate scenarios, the area of the glacier in most regions is in a relatively stable state, about 18.16–27.62% of the total reference year glacier area is in an alternating change of melting and accumulation, and of which few glaciers are increasing, but this does not change the overall retreat trend of the glacier in the study area. Our study offers momentous theoretical value and practical significance for enriching and expanding the theories and analytical methods of the glacier change.

**Supplementary Materials:** The following are available online at <https://www.mdpi.com/article/10.3390/w13111541/s1>. File S1: Final sampling point distribution across altitudes/annual precipitation/mean annual air temperature; File S2: Correlation analysis of environmental factors.

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Data processing. Z.K., H.C., X.Z.: Visualization, Investigation, Validation. All authors have read and agreed to the published version of the manuscript.

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