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Analysis of temporal and spatial heterogeneity of glacier mass balance on the northern and southern slopes of the Central Tianshan Mountains, China

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Abstract: Glacier mass balance can ~~visually~~ indicate the degree of glacier response to climate change. The mountain glaciers are an essential source of recharge for rivers in arid regions and play a vital role in maintaining regional ecological stability and production life. This paper drives a spatially distributed degree-day model using multi-source remote sensing data such as MOD11C3 and TRMM3B43 to simulate the mass balance in the Tianshan mountains' south and north slope basins. And the Spatio-temporal heterogeneity of the mass balance was compared and attributed using Geodetector. The results show that: (1) The glacier area in the Manas river basin is more significant than that in the Kaidu river basin. (2) During 2001-2016a, the glaciers in the south and north basins continued to melt and were in a negative balance state (-465.95 mm w.e.), with an interannual change rate of-28.36 mm w.e./a. The track of the mass balance in both basins was similar with time, but the ~~volatility~~ of the Manas river basin was more substantial than that in the Kaidu river basin. (3) ~~Climatic factors dominate changes in the mass balance in both basins, but the glacier mass balance in the Kaidu river basin is more dependent on climatic factors.~~ (4) Regarding glacier accumulation and ablation areas, climatic factors still dominate the factors affecting glacier accumulation and ablation in both basins. ~~Still,~~ topographic factors also contribute to the mass balance in the accumulation area in the Kaidu river basin and the ablation area in the Manas river basin, respectively. This study contributes to analyzing the mechanism of regional changes in the glacier mass balance. It provides a scientific basis for investigating the characteristics of water resources changes and water resources regulation in the north and south slope basins of the Tianshan Mountains.

Keywords: Manas River Basin, Kaidu River Basin, glacier mass balance, Geodetector, attribution analysis

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1. Introduction

With global warming, as significant freshwater resources are known as "solid reservoirs", most glaciers are in a state of retreat and ablation. Some studies have also shown that mountain glaciers are more sensitive to climate warming[1,2]. As an indicator of climate change, glaciers mass balance is a critical junction connecting glaciers and climate, and it also comprehensively reflects the hydrothermal conditions of glacier development[3,4]. Glacier meltwater generated by the change of glacier mass balance has a stabilizing effect on regional water resources. Given the importance of glacier mass balance, it has been an important research content in glacier change detection worldwide. The World Glacier Monitoring Service (WGMS) aims to monitor global glacier changes continuously, systematically compile global glacier monitoring data, make long-term observations of 10 key reference glaciers, and publish their mass balance data every two years[5]. Urumqi Glacier No.1, located in the Tianshan Mountains in Central Asia, is one of the reference

glaciers included in the ten essential monitoring items of WGMS, which can reflect the basic characteristics of the changes in central Asian glaciers to a certain extent [6,7]. However, affected by topography and regional climate conditions, the monitoring data of a single glacier cannot comprehensively reflect the overall change characteristics of regional glaciers. Selecting suitable regions to reflect the spatial heterogeneity of glacier mass balance changes can further explain the internal factors affecting the changes in the mass balance of mountain glaciers, which will be more conducive to understanding the mechanism of their recharge to rivers.

The research methods about glacier mass balance mainly include field observation, remote sensing monitoring, model simulation, ~~etc.~~[8-10], glacier surface observation can provide detailed parameters. Still, it is difficult to reflect the spatial heterogeneity of the region due to the significant human interference in the observation process, which is usually confined to a single glacier in some areas. In addition, remote sensing monitoring has the advantages of a wide range and multiple time series. Still, when glacier surface elevation changes are directly monitored to reflect ablation and accumulation, it is difficult to guarantee the accuracy of the region with weak modifications, which is prone to large deviations[11]. Compared with glacier observation and remote sensing monitoring, model simulation can better reflect the physical process mechanism of mass balance[12,13], which can be divided into the empirical model based on the degree-day factor and the physical model based on energy balance. Compared with glacier observation and remote sensing monitoring, model simulation can better reflect the physical process mechanism of material balance[14] and can be divided into empirical models based on degree-day factors and physical models based on energy balance. The energy balance model is based on the energy balance principle, considers the energy input and output items, and focuses more on the mechanism of the material balance process. However, the input parameters and variables are complex and challenging to obtain. There are high requirements for data accuracy or resolution, which limits the popularization and application of the model. The degree-day model is simple and easy to obtain, its results are accurate and reliable in large-scale glacier studies, and it is most widely used. By comparing and analyzing numerous models and methods, the degree-day model regards the degree-day factor as a statistical variable of albedo, latent sensible heat flux, relative humidity, and other factors. And degree-day model adopts a constant representation according to the difference in time and space, which effectively reduces the model's complexity. Therefore, if a large scale glacier material balance study is to be carried out, taking into account factors such as topography and climate, and taking into account the advantages of the simplicity and universality of the degree-day model and the good balance of the ice melt/snowmelt module, a degree-day model based on the water balance principle is more suitable for the model. [15].

As an ecological barrier of an oasis in the arid area of northwest China, the dynamic change of glacier mass balance in Tianshan Mountain is of great scientific value in assessing the impact of climate on water resources[8]. The Tianshan Mountains in China are 250-350 km wide from north to south, which is the most extensive independent zonal mountain system globally, the farthest mountain system from the ocean globally, and the most major mountain system in the arid region of the world. At present, the study of glacier mass balance in The Tianshan Mountains of China is mainly limited to the analysis of measured data of a single glacier, the simulation of glacier material balance in different regions or the whole basin, and the impact of climate change on regional material balance [16-19]. There are few studies on the difference and comparison of glacier mass balance in the same mountain system under different site conditions. The regional differences in ecological and geographical characteristics on the northern and southern slopes of the Tianshan Mountains affect the development and evolution of glaciers in different regions, leading to varying factors of glacier mass balance changes in the different areas. ~~Suppose we can choose appropriate basins on the northern and southern slopes of the Tianshan Mountains as the comparative study area.~~ In that case, we can explore the leading factors

affecting the glacier mass balance in the northern and southern slopes of the Tianshan Mountains through Geodetector and make a comparison to explain further the mechanism of the change of mountain glaciers' mass balance. In this paper, glaciers in the Manas River Basin on the Northern Slope of the central Tianshan Mountains and the Kaidu River Basin on the southern slope are selected as research objects. Using MOD11C3 and TRMM3B43 as driving data, a spatially distributed degree-day model was constructed to analyze and compare the mass balance of glaciers in typical watersheds on the north and south slopes of Geodetector to make an attribution analysis of their spatiotemporal heterogeneity characteristics. This study is helpful to analyze the mechanism of regional changes in mountain glacier mass balance and provides the scientific basis for exploring the features of water resource change and water resources regulation in the northern and southern slopes of the Tianshan Mountains.

2. Study Area

Tianshan Mountain, located in the hinterland of Eurasia, is the most extensive independent latitudinal mountain system in the world, which stretches for more than 1,700 meters in China. It crosses the central part of Xinjiang Uygur Autonomous Region and is the boundary between northern and southern Xinjiang [20]. It consists of parallel mountain ranges divided into north, middle, and south zones. The study area is located in the central Tianshan Mountains, including the Yilianhabierga Mountains, Saarming Mountains, Bortoula Mountains, etc. Yilianhabierga Mountains are about 320 km long in the east and west, 110 km wide in the north and south, and the mountains are generally above 4000 m above sea level[21]. The Manas River on the northern slope and the Kaidu River on the southern slope selected in this study are derived from Mount Ylianhabirga (Figure. 1). The south slope of Tianshan Mountain has less precipitation, is deep inland, and has an arid climate. The north slope of Tianshan Mountain has more precipitation than the southern slope because of the humid airflow from the Arctic Ocean and the Atlantic Ocean. The climate is relatively moist. The southern slope has sufficient sunlight, but the northern slope is less, and the temperature of the south slope is higher than that of the north slope. Manas River Basin, located on the north slope of the middle section of Tianshan Mountain, is the basin with the most significant number and scale of glaciers in the inland area of Junggar and has a moderate temperate continental arid climate[22,23]. The Kaidu River, located on the southern slope of the central Tianshan Mountains, is one of the four primary sources of the Tarim River Basin, the longest inland river in China, and belongs to the warm temperate continental arid climate[22,23].

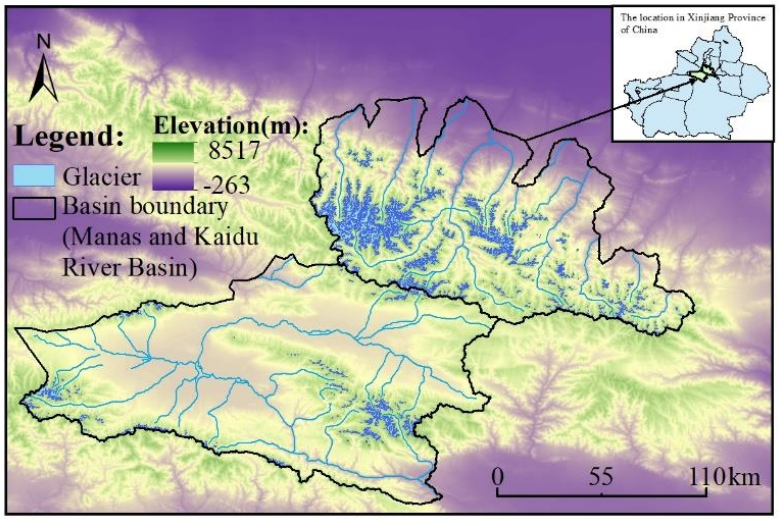


Figure 1. Location of the study area

3. Data and Methods

The data of this paper are divided into multi-source remote sensing data, glacier area, and boundary vector data of the Manas river basin and the Kaidu river basin. Remote sensing raster data include DEM, MOD11C3, MOD09Q1, TRMM3B43, ≥0°C accumulated temperature, precipitation, air temperature, solar radiation, etc. (Table 1). The specific applications of the data in this paper are as follows: DEM can reflect the topographic characteristics of mountainous areas and can be used to obtain topographic factors in mountainous regions, which is the basis for the spatial discretization of various factors of glacier mass balance to construct degree-day model, and it is also a factor that affects the change of glacier mass balance. MOD11C3 and TRMM3B43 are monthly data from 2001 to 2016a, the primary meteorological data driving the distributed degree-day model. The MOD09Q1 surface reflectance data are used to represent the difference in the absorption and reflection of solar radiation by ice and snow, which is the critical parameter for the inversion of ice-snow degree-day factor on the glacier surface. The climatic background data such as ≥0℃accumulated temperature, precipitation, air temperature, and solar radiation are put into the Geodetector and the terrain factors as climate factors to explore the reasons for the changes in the glacier mass balance. The glacier area vector data come from the Second China Glacier Catalog Dataset.

Table 1. Data sources.

Type of Data	Resolution	Data Sources
DEM	30m×30m	RESDC（ https://www.resdc.cn/data.aspx?DATAID=217）
MOD11C3	0.05°×0.05°	NASA（https://lpdaac.usgs.gov/products/mod11c3v006/）
MOD09Q1	250m×250m	NASA（https://lpdaac.usgs.gov/products/mod09q1v006/）
TRMM3B43	0.25°×0.25°	NASA（https://disc.gsfc.nasa.gov/datasets/TRMM_3B43_7/）
≥0°C accumulated temperature	1km×1km	RESDC(https://www.resdc.cn/DOI/doi.aspx?DOIid=39)
air temperature	1km×1km	
precipitation	1km×1km	
solar radiation	10km×10km	TPDC(https://data.tpdc.ac.cn/)
The Second China Glacier Catalog Dataset	30m×30m	NCDC(http://www.ncdc.ac.cn/)

3.1. Simulated glacier material balance

The degree-day model simplifies the process mechanism of glacier ablation and accumulation. Still, the traditional degree-day model is only a conceptual model. In contrast, the distributed model improves the ability to express the spatial characteristics of each element in the degree-day model, enhances its physical basis, and divides the glacier area into grids. The spatial variation of the overall glacial mass balance is illustrated by describing the specific variation of each grid cell in terms of a set of factors that affect the variation of the glacial mass balance. This way shows the spatial change of the entire glacier mass balance[24]. Due to the different resolutions of the multi-source remote sensing data driving the distributed degree-day model, it is difficult to describe the ice surface climate with too low resolution. Therefore, in this study, the OLS model was constructed in the process of modeling the distributed degree-day model to downscale MOD11C3 and TRMM3B43 to 250m×250m to meet the model accuracy requirements. In contrast, the distributed degree-day model reflects the spatial variation characteristics of the mass balance through the grid.

For the ablation of glacier ice and snow, the amount of ablation in a certain period is expressed as follows[12,13,25,26]:

$$A = D \cdot PDD \quad (1)$$

Where A is the ablation of water equivalent of glacier ice and snow in a certain period (mm we). D is the degree-day factor of glacier ice/snow (mm d^{-1} $℃^{-1}$). PDD is the positive accumulated temperature in a certain period. It can be obtained by the following formula[27]:

$$PDD = \int_{N_1-1}^{N_2} \frac{1}{\delta\sqrt{2\pi}} \int_0^{+\infty} T_m e \frac{-(T_m - T_a)^2}{2\delta^2} dT dt \quad 2)$$

Where it is assumed that the monthly average temperature (°C) within the year is usually distributed, Ta is the annual average temperature (°C), δ is the standard deviation of the temperature distribution, N1、N2 are the start and the end dates of the calculation, and the period is $N = N_2 - N_1 + 1$。

The net mass balance at a point (or height) is[25]::

$$Bi = P + A + f \quad (3)$$

Where Bi is the glacier mass balance in a certain period (mm we). P is the accumulation amount of the glacier surface in a certain period, that is, the solid precipitation (mm). A is the amount of ablation. f is the amount of meltwater infiltration and freezing or internal supply (mm we), usually calculated as 10% of the ablation volume.

The solid precipitation can be calculated according to the limiting temperature method[28]:

$$P_s = \begin{cases} P & T \le T_S \\ \frac{T_L - T}{T_L - T_S} P & T_S < T < T_L \\ 0 & T \ge T_L \end{cases} \quad (4)$$

$$P_L = P - P_S \quad (5)$$

Where P_s and P_L are the solid and liquid precipitation (mm), P is the total monthly precipitation (mm). T is the monthly average temperature (°C), T_S and T_L are the limiting temperatures of solid and liquid precipitation (°C). Usually, it can be determined according to the observation results of Urumqi glacier No.1 in the Tianshan Mountains and related literature, and take -0.5 °C and 2 °C, respectively.

3.2. Attribution of glacier ~~material~~ balance change

The Geodetector can effectively explain the spatial coupling between geographic phenomena and multiple factors[29-31]. In this paper, the factor detection module of the Geodetector is used to quantitatively detect whether the factors affect the spatial heterogeneity of the changes in the glacier mass balance in the study area and determine the degree of influence of each factor. The formula is as follows:

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N\sigma^2} = 1 - \frac{SSW}{SST} \quad (6)$$

Where h=1, 2, …, L is the stratification of the variable Y or factor X, the classification or partition. N_h and N are the number of units in the h stratum and the whole area, respectively. $\sigma_h^2$and σ^2 are the variances of the stratum h and the whole area Y. SSW and SST are

the sums of the conflict within the layer and the total friction of the whole area, respectively.

The factors affecting the change of glacier mass balance are diverse, and the internal mechanisms are complex, but they can be roughly classified into two major factors: topography and climate. Topographic factors mainly include altitude, slope, slope aspect, etc., and climatic factors mainly comprise air temperature, precipitation, accumulated temperature, solar radiation, etc.[2,32-34]. Each factor is coupled and influenced by each other, which affects the changes in the glacier mass balance. In particular, the hydrothermal conditions and terrain complexity of the north and south slopes of the Tianshan Mountains will further cause spatial differences in the glacier mass balance on the north and south slopes[35,36]. Through the factor detection of Geodetector, the q value of the above factors in each geographical area is calculated and sorted. The higher the q value is, the stronger the explanatory power of the factor for the change of glacier mass balance is. According to the contribution rate, the driving factors of glacier mass balance change in northern and southern slopes can be identified and attributed.

4. Results

4.1. Analysis of glacier area in the middle part of the Tianshan Mountains

Glacier area data are derived from the Second China Glacier Catalog Dataset, which is used to determine the distribution of glaciers in each basin during the material balance calculation, and also as the basis for calculating the glaciers mass balance of individual glaciers. In order to know the distribution of glacier's area in the vertical direction, all the glaciers in both basins were arranged according to their average elevation, which found that most of the large glaciers are located at high elevations and are concentrated. Still, the number is generally small, while the small glaciers are located at low elevations but are widely distributed and numerous (Figure. 2). At the same time, glacier area is the most intuitive manifestation of glacier size. The glacier size of each elevation zone can also be known by counting the glacier area in each elevation zone, which influences the change of mass balance. When the glacier size is large, it can effectively restrain the glacier melting. While the glacier size is small[37], it is easier to melt. The lowest elevation range of glaciers' distribution in both basins is 3500 ~ 3700 m, the highest is 4500 ~ 4800 m, and most of the large-scale glaciers are in the range of 3900 ~ 4300 m. The total area of glaciers in 4100 ~ 4300m is the highest, about 560 km^2, the 3900 ~ 4100m is the second elevation range, and the area in 3500 ~ 3700m is the least, which is less than 20km^2. The glaciers in the Kaidu river basin are mainly concentrated in the southwest and northeast of the basin. In contrast, the glaciers in the Manas river basin are focused on the southern part of the basin. The number of glaciers in the Manas river basin is 2.7 times that of the Kaidu river basin. The maximum area of a single glacier in the Manas river basin is 36 km^2, while that in the Kaidu river basin is 16 km^2. Overall, the total volume of glaciers in the Manas river basin is more extensive than those in the Kaidu river basin.

Generally speaking, small glaciers are the most sensitive to climate change, and their change of mass balance is the most pronounced. Therefore, the glaciers in both basins are divided into 11 classes according to the area size, with 0.001, 0.003, 0.005, 0.1, 0.5, 1, 5, 10, 15, 20, and 40 km^2. Although there are some differences in the number of glacier bars between both basins, glacier size distribution is very similar. There are a lot of glaciers in both basins, which are smaller than 1km^2, with peak numbers occurring between 0.01 and 0.03 km^2. At the same time, it can be found that the larger area of glaciers in both basins, the fewer number with an area of more than 10 km^2. And there is no glacier with an area of more than 20 km^2 in the Kaidu river basin. In addition, the small glaciers are more likely to melt because of their isolation and distribution in low altitudes. So the key to maintaining the mass balance of glaciers in both basins is the existence of a small number of medium and large area glaciers. The cooling effect on the surrounding environment due to the large size of the glacier can have a mitigating effect on glacier melt.

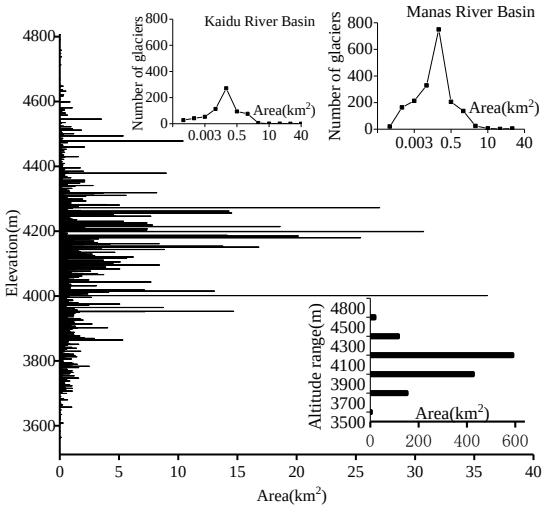


Figure 2. Elevation distribution characteristics of single glacier area in the northern and southern basins of the Central Tianshan Mountains

4.2. Changes in the spatial and temporal distribution of glacial resources in Xinjiang

Based on China's Second Glacier Cataloguing data, the mass balance of a single glacier in the Manas River Basin and the Kaidu River Basin was compared and analyzed (Figure 3). Overall, the mass balance of glaciers in the middle Tianshan Mountains is mainly distributed between 0-1000mm w.e., and the number of glaciers in -1000-1500mm w.e. is significantly lower than former, and the number of glaciers between -2000mm w.e. and 0 mm w.e. is the least. It can be seen that the mass balance of the glaciers in the middle Tianshan Mountains is dominated by negative balance, and the distribution characteristics are similar to the normal distribution. The glaciers in a positive balance in the Kaidu river basin are significantly less than those in the Manas river basin. Still, the mass balance of most glaciers in the Kaidu river basin is between 0 and -500mm we, while The mass balance of most glaciers in the Manas River Basin is between 0 and -1000 mm w.e.. And there are more glaciers in the Manas river basin with a mass balance of over -1500 mm w.e than in the Kaidu river basin. The maximum value of the mass balance of glaciers in the Kaidu river basin is comparable to that of the Manas river basin. Although the glaciers' material balance spans in both basins are similar, the Manas river basin has more glaciers and a higher negative balance.

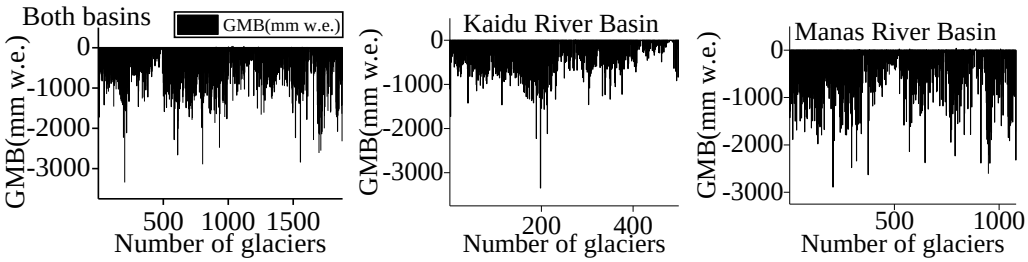


Figure 3. The mass balance of a single glacier in the north-south watershed of the middle Tianshan Mountains

The interannual changes in the mass balance of glaciers can show the overall changes in the watershed and more clearly reflect the regional changes in mass balance (Figure 4). During the study period, the glaciers in both basins were in a negative balance state and continued to melt (-465.95 mm w.e.), with an inter-annual variation rate of -28.36 mm we/a. The most obvious glacier ablation was in 2010, followed by 2014; The melting trend can be divided into two stages: 2001-2010a is a continuous increase, and 2010-2016a is weakened volatility. Comparing both basins, from 2001 to 2016, the glacier ablation in the Kaidu river basin was 3.79% higher than that in the Manas river basin, but the change rate

of the glacial mass balance in the Manas river basin (-28.85 mm w.e./a) slightly higher than the Kaidu tiver basin (-26.34 mm w.e./a). Glacier ablation in both basins reached the highest value in 2010, and the ablation in the Kaidu river basin (878.89mm w.e.) was higher than that in the Manas river basin (811.26mm w.e.). The trajectories of material balance in both basins are similar with time. Still, the volatility of the trajectory in the Manas river basin is higher than that of the Kaidu river basin, with only a 1.07mm w.e. difference. According to its spatial distribution map(Figure 4), the high value of glacier increased mass balance in both basins appears at the glacier aggregation region. The low mass balance values are mainly distributed at the end of glaciers or in clusters of small glaciers. The melting risk of dispersed glaciers is higher than that of glaciers with a high aggregation degree. It is not difficult to find that the glaciers on the southern slope are smaller in size, but the average ablation volume is higher than that on the northern slope, and the glaciers on the north slope are larger in scale but have higher ablation rates than those on the southern slope. This regional difference is closely related to the hydrothermal conditions and topographic conditions of the northern and southern slopes of the Tianshan Mountains.

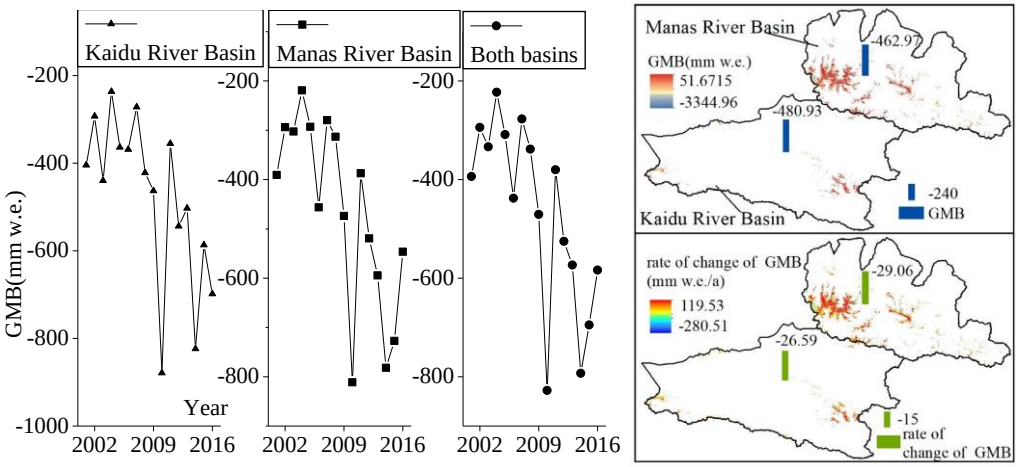


Figure 4. Glacier mass balance in the north-south watershed in the middle Tianshan (2001-2016)

In mainly glacier research, the Tianshan glaciers, as the representative of continental glaciers, play a pivotal role. Many scholars have carried out many types of research on changes in the mass balance of some glaciers in various basins in Tianshan mountains. Among them, Wucheng, X. et al. estimated the mass balance of the Tianshan glaciers in China based on the Landsat and ICESat data from 2003 to 2009a. They concluded that the average mass balance of the Tianshan Mountains during the period was -120mm w.e. [38]. However, their estimated results were small compared with this study. Xiaohui, H. et al. used the geodetic method to estimate that the average mass balance of glaciers in the Tu-Haalik area from 1972 to 2016a was 180 mm w.e.. Still, during the period from 1999 to 2016a, it reached 360 mm w.e. [39], which is far greater than the previous value of glacier mass balance, demonstrating the accelerated loss of glaciers since 2000. Ninglian, W. et al. collected the latest results of recent research on the mass balance of glaciers in the Tianshan Mountains. They found that the average mass balance of the Junggar basin was 600 mm w.e. [40], which was slightly larger than that of the present study. In addition, Puyu; W. et al. estimated that from 1972 to 2011a, glacier No. 6 in Yushugou, Miaoergou, and No. 1 glacier in Urumqi Heyuan in the East Tianshan Mountains were -510 and -510 mm w.e. [41]. Yanjun, C. et al. obtained the average mass balance of the Qingbingtan No. 72 glacier in the South Tianshan Mountains from 2008 to 2014a to be -510, -510, and -380 mm w.e. , respectively[42], which are similar to the results of this study.

4.3. The attribution of Glacier mass balance change in the North-South Slope Basin in the Middle Tianshan Mountains

By using factor detection and interaction detection based on Geodetector, the dominant factor affecting the material balance can be determined by ranking the factor q-value (Table 2). The detector found that the dominant factors affecting the change of mass balance in the basin can be classified into topography and climate. Altitude is an important factor affecting the mass balance in the study area, followed by>0°C accumulated temperature and annual average temperature. The contribution of annual average precipitation to solar radiation is equivalent. Topographic relief, slope, and aspect have limited influence on mass balance change. The contribution rate of topographic factors to both basins reached 44.87%, slightly lower than that of climatic factors (51.27%). Therefore, the climate factor is still the dominant factor affecting the change of glacier mass balance in both basins. Although independent climatic factors have less influence than altitude, the interaction and coupling of each factor will have a stronger effect on glacier mass balance change.

Table 2. Contribution rate of mass balance factor affecting glacier (%).

Basins	Elevation	Topographic relief	Gradient	Aspect	Solar radiation	Air temperature	Precipitation	> 0 °C accumulated temperature
Both Basins	42.75	1.06	1.07	3.85	11.08	14.41	10.14	15.64
Kaidu	30.88	0.77	0.79	2.09	14.73	11.31	26.90	12.53
Manas	40.44	1.02	1.02	3.85	11.00	14.70	8.02	19.95

The most critical factor affecting mass balance in the Kaidu river basin is altitude, followed by precipitation and its contribution rate is equivalent to altitude, reaching 26.9%. It shows that the precipitation factors greatly influence the glacier mass balance in the Kaidu river basin. The contribution of solar radiation, air temperature, and accumulated temperature is not much different. The contribution rate of slope direction is slightly higher than that of topographic relief and slope, but the contribution rate of the three is the low value of the whole factors. The contribution rate of topographic relief to the slope is less than 1% in the Kaidu River Basin. The contribution rate of factors affecting glacier mass balance in the Manas River Basin is higher than 1%. The first factor is still altitude, with the contribution rate of 40.45 %, followed by the accumulated temperature of > 0 °C. The contribution rate of solar radiation to temperature is equivalent, and the precipitation's contribution rate is slightly lower than the first two factors. Similar to the Kaidu river basin, the contribution rate of topographic relief, slope, and aspect are also low. Still, the contribution rate of the three in the Manas river basin is slightly higher than that in the Kaidu river basin, and the contribution rate of the slope is 3.85%. In the overall role of topographic factors and climatic factors, the Kaidu river and Manas river basin are the same, still dominated by climatic factors. However, in the Kaidu river basin, the contribution rate of the climate factor is nearly 20% higher than that of the topographic factors. Manas river basin's climate factors contribution rate is only 7.3% higher than the topographic factors, which is closely related to the more complex topographic environment in the Manas river basin. Because the Manas river basin is located on the northern slope of the Tianshan Mountains, the precipitation is relatively abundant (annual average precipitation is 257.5 mm), reducing the warming effect of solar radiation on glaciers. And the average elevation in the basin is 4094m. The large glaciers are mostly large distributes at high altitudes, which is more conducive to their accumulation, alleviating the Manas river basin's glacier ablation. There are few large glaciers in the Kaidu river basin, mainly distributed as small glaciers, and the average elevation of a single glacier in the basin is 3984 m. Glacier positive equilibrium is limited. Although the precipitation is less than in the Manas river basin, precipitation is liquid mainly at low altitudes, so it is difficult to stay on small glaciers. Higher heat in water droplets can accelerate the melting of small glaciers and increase their negative balance. According to the calculation, the ice climate data of

both basins are obtained, and the average annual temperature of the glacier in the Manas river basin is -13.1 °C. In comparison, the Kaidu river basin is -9.7 °C. The main reason is that the Kaidu river basin is located on the southern slope of the Tianshan Mountains. Its solar radiation is higher than that of the Manas river basin, with a value of 179.29 W / m². The accumulated temperature above 0 °C is 337.6 °C, which is significantly higher than the Manas river basin (182.5 °C) on the northern slope of the Tianshan Mountains. Under the combined effect of topography and climate factors, the negative balance intensity of the Kaidu river basin is higher than that of the Manas river basin.

Under the dual influence of climatic factors and topographic factors, the glaciers in both basins of the middle Tianshan Mountains are melting. Still, there are some differences in the dominant factors affecting the melting of glaciers on the northern and southern slopes. The terrain on the south slope of the Tianshan Mountains is relatively flat and has a less natural place for glacier development. The limited precipitation cannot effectively accumulate glaciers at high altitudes, and temperature and solar radiation are higher than those on the northern slope, which is more likely to promote glacier ablation. Glacier ablation is more than on the north slope. Because of the complex terrain and more large glaciers on the north slope, such conditions effectively alleviate the glacier's negative balance, and thermal energy mainly affects ablation factors. The precipitation has a particular effect on large glaciers or upstream glaciers in the basin, but the influence ability is limited.

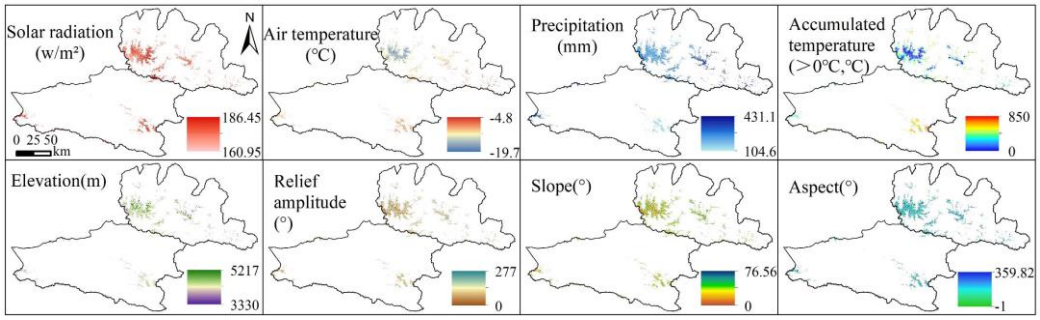


Figure 5. Driving factors affecting glacier mass balance

5. Discussion

The changes in the mass balance of glaciers are affected by various influencing factors. These factors will also produce corresponding eigenvalues in mass balance changes, and different degrees of mass balance will be adapted to other climatic, topographical conditions. If the attribution comparison is based only on the mean value of the mass balance of glaciers in the region, the attribution analysis of glacier accumulation and ablation (positive and negative mass balance) in the basin is very likely to be ignored. This paper takes the positive and negative balance as the breakthrough point, combining it with the factor detection of the Geodetector and comparing the differences between both basins. The mechanisms for glacial mass balance changes on the north and south slopes of the middle Tianshan mountains can be further refined. The glaciers were divided into positive and negative balance areas based on the balance value by distributed degree-day model. Using the Geodetector to detect the contribution rate of each factor. The driving force of the positive and negative balance areas in both basins will be further discussed.

5.1. Contribution Analysis of Influencing Factors Based on Positive and Negative Mass Balance Zones

The part in positive balance is considered the accumulation area, and the part in negative balance is regarded as the ablation area based on the value of glacier mass balance. From the results of the Geodetector (Table 3), the factors affecting the accumulation of glaciers in the two basins are dominated by climatic factors. The cumulative contribution rate of climate factors is 69.37%, of which the precipitation contribution rate is the highest,

followed by the contribution rate of temperature. The contribution rate of solar radiation is only 3.09%, and the effect of solar radiation on the accumulation of glaciers is minimal. Among topographic factors, altitude still has a high contribution rate (26.53%), while the contributions of the other three topographic factors are all low (Table 3). For glacier accumulation areas, hydrothermal conditions are critical factors. Mountains provide a basic place for glaciers to accumulate/develop. It is possible to have a certain accumulation effect on glaciers. In the context of climate warming, the continuous melting of glaciers is a significant trend; the accumulation area of glaciers is mainly concentrated on the main body of glaciers with higher altitudes and larger scale, and they have the characteristics of seasonal accumulation[43-45]. The climate factor is still dominant (52.2%), but its cumulative contribution rate is equal to the topographic factor (47.8%). Among the climatic factors, the precipitation factor has the highest contribution rate (17.73%), followed by the solar radiation factor (14.85%). Among the topographic factors, the altitude contribution rate is the highest, which is 38.32%. The remaining three topographic factors have a low contribution rate to the ablation area. Different from the accumulation area, the elevation factor is the factor with the highest contribution to the negative balance of glaciers in the whole basin.

Table 3. Each factor's statistical value and contribution rate in the accumulation/ablation zone in the middle Tianshan Mountains.

Area	GMB (mm/w.e.)	Elevation (m)	Topographic relief (°)	Gradient (°)	Aspect (°)	Solar radiation (W/m²)	Air temperature (℃)	Precipitation (mm)	> 0 ℃ accumulated temperature (℃)
Accumulation	30.21	4502.18	60.19	37.67	128.92	157.41	-14.16	241.94	128.84
Contribution (%)	—	26.53	1.78	0.84	1.48	6.92	28.95	30.41	3.09
Ablation	-718.97	3980.93	37.64	25.34	187.71	175.67	-11.45	254.88	260.91
Contribution (%)	—	38.32	1.86	1.95	5.67	11.39	9.82	8.10	16.59

Under the comprehensive action of multiple factors, there are significant differences in the natural environment in the positive and negative balance areas of the north and south slopes of the middle Tianshan. According to statistics, the accumulation area is 33.3 km², the ablation area is 860.13 km², and the mass balance of the ablation area is dominant (Table 3). The topographic complexity of the accumulation area is higher than that of the ablation area, and the high altitude directly weakens the temperature of the environment in the accumulation area. The complex topographic relief is very likely to form the mountain's shadow to block the sunlight, thus eliminating the direct effect of solar radiation on the glacier surface and reducing the potential risk of glacier endothermic melting[46,47]. As shown in Table 3, the temperature and precipitation in the accumulation area are significantly lower than those in the ablation area. Most accumulation areas face the southeast, while the ablation areas are mostly facing the south. Therefore, the solar radiation received by the accumulation area is lower than that of the ablation area. The ablation area is mainly located in the lower altitude area, and the end of the glacier is straightforward to be ablated. The terrain here is relatively flat and more susceptible to solar radiation. Although the average temperature for many years is -11.45°C, the accumulated temperature >0°C is significantly higher than that in the accumulation area. It also has a higher risk of melting and is characterized by significant seasonal ablation.

5.2. Attribution comparison of both basins based on positive and negative balance areas

The geographical environment of the Manas river basin on the northern slope of the Tianshan Mountains is quite different from that of the Kaidu tiver basin on the southern slope. The formation of positive and negative balance areas in the basins are also different, which can be further revealed through comparative analysis of the internal mechanism of the spatial heterogeneity of the mass balance of Tianshan glaciers. Topographic factors dominate the accumulation area and ablation area in the Kaidu river basin, and the ablation area is dominated by climatic factors, with cumulative contributions of 55.2% and 70.84%, respectively. The accumulation area in the Manas river basin is dominated by climatic factors, with a cumulative contribution rate of 69.38%, and the ablation area is dominated by topographical factors, with a cumulative contribution rate of 54.1% (Table 4). The natural conditions of both basins control the patterns of glacier mass balance in the basins so that the dominant factors are distinctively regional.

Table 4. Statistical value and contribution rate of each factor in the accumulation/ablation area of the Manas and Kaidu river basins.

River basin	GMB (mm/w.e.)	Elevation (m)	Topographic relief (°)	Slope (°)	Slope aspect (°)	Solar radiation (W/m²)	Temperature (℃)	Precipitation (mm)	> 0℃ accumulated temperature (℃)
Accumulation area									
Kaidu	20.37	4346.73	52.94	33.90	135.01	170.08	-9.16	138.38	400.76
Rate (%)	—	11.64	10.11	22.06	11.39	12.70	7.93	9.85	14.32
Manas	31.18	4517.40	60.90	38.04	128.33	167.11	-14.65	252.08	102.21
Rate (%)	—	10.25	5.80	3.08	11.49	16.31	23.73	12.64	16.70
Ablation area									
Kaidu	-591.73	3944.43	36.80	24.79	184.22	178.11	-9.78	219.20	333.47
Rate (%)	—	24.43	0.96	1.20	2.57	12.95	14.07	28.33	15.49
Manas	-769.77	4006.34	38.06	25.62	189.70	174.71	-12.12	268.97	231.87
Rate (%)	—	43.05	1.69	2.16	7.20	11.39	9.82	8.10	16.59

In the accumulation area, the Manas river basin's positive mass balance and topographic complexity are higher than the Kaidu river basin (Table 4). It is worth noting that the slope factor has a very high explanatory power (22.06%) in the accumulation area of the Kaidu river basin, which may be related to the easy retention of solid snowfall on gentle slopes[48,49]. The accumulation area in the Manas river basin has the highest contribution rate of air temperature (23.73%). Taking into account factors such as more glaciers and larger scales in the Manas river basin, and then comparing climate data such as temperature and precipitation, it can be inferred that the stability of glaciers in the Manas river basin in the accumulation zone is higher and the surrounding environmental conditions are more conducive to the formation of positive mass balance of glaciers than those in Kaidu river basin. In the ablation area, the difference between both basins in the statistics value of the factors is slight. Still, the negative mass balance value of the Manas river basin is higher. The highest contribution rate of precipitation factor in the Kaidu river basin (28.33%) was slightly higher than that of elevation. The highest contribution rate of elevation factor in the Manas river basin (43.05 %). Glaciers ablation is partly due to seasonal liquid precipitation at low altitudes[50-52]. And the mean elevation of the ablation area in the Manas river basin is similar to that of the Kaidu river basin. The altitude range of about 3900-4000m can be seen as a strong ablation zone in both basins. Although the dominant factors of the ablation/accumulation areas between both basins are different, in the final analysis, the interaction and coupling between topographic and climatic factors cause the differences in the mass balance of the glaciers in the basins.

In this study, comparing the differences in mass balance in the basins failed to go to a more detailed time scale. It focused on discussing natural environmental factors on the mass balance of glaciers between both basins without considering the direct or indirect effects of human activities on glaciers.

6. Conclusions

This paper uses distributed degree-day model driven by multi-source remote sensing data. It simulates the glacier mass balance of the south and north basins of the Tianshan mountains from 2001 to 2016. Based on the analysis and comparison of the temporal and spatial changes, using eight factors, including terrain factors and climate factors, were introduced by Geodetector to conduct an attribution comparison from the basin scale and the positive and negative mass balance area scale in the basin. The conclusions are as follows:

(1) On the overall scale, glaciers in the Manas river basin are larger than those in the Kaidu river basin. However, the number of large glaciers in both basins is less, and the number of glaciers with an area of more than 10 km^2 is relatively rare in both basins, and there are no more than 20 km^2 of glaciers in the Kaidu river basin.

(2) During the study period, the glaciers in both basins continued to melt and were in negative mass balance(-465.95 mm w.e.) with an interannual variability of -28.36 mm w.e./a. The overall trend of the melt can be divided into two phases: 2001-2010a for continuous enhancement, 2010-2016a for fluctuations weakened. Compared with the northern and southern basins, the ablation of the glacier in the Kaidu river basin is 3.79% higher than that in the Manas river basin, but the change rate of glacier mass balance in the Manas river basin (-28.85 mm w.e./a) is slightly higher than that in the Kaidu river basin (-26.34 mm w.e./a). The glacier mass balance of the north and south basins varies similarly over time. Still, the volatility of the yearly mass balance Manas river basin is stronger than that of the Kaidu river basin. The high value of the mass balance of glaciers in both basins occurs at the area of glacier aggregation. And the low value of mass balance is mainly distributed at the end of the glacier or in the area of the cluster of small glaciers, so the priority of dispersed glaciers in the ablation stage is higher than that of high aggregation glaciers.

(3) Like the overall basin attribution results, the mass balance changes in the Kaidu river and Manas river basins are still dominated by climatic factors. However, in the Kaidu river basin, the contribution rate of the climate factor is nearly 20% higher than that of the topographic factor. The contribution rate of climate factors in the Manas river basin is only 7.3%, so the glacier mass balance in Kaidu river basin is more dependent on climate factors.

(4) The factors affecting glacier accumulation within both basins are dominated by climatic factors, with a cumulative contribution of 69.37%. In contrast, the glacier ablation area is dominated by climatic factors (52.2%). Topographic factors dominate the accumulation area in the Kaidu river basin, and climatic factors dominate the ablation area. The dominant factors of the Manas river basin in the accumulation/ablation area are opposite. The stability of glaciers or some parts of glaciers in the accumulation area of the Manas river basin is higher. The driving intensity of various factors in the ablation area of both basins is similar.

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References

1. Garg, V.; Kudekar, A.R.; Thakur, P.K.; Nikam, B.R.; Aggarwal, S.P.; Chauhan, P. Glacier Change Studies under Changing Climate Using Geospatial Tools and Techniques. Journal of the Indian Society of Remote Sensing. 2021, 49.
2. Xingran, C.; Zhongqin, L.; Hui, Z.; Chunhai, X. Vulnerability of glacier change in the Tianshan Mountains region of China. Journal of Geographical Sciences. 2021, 31.
3. Xingran, C.; Chunhai, X.; Zhongqin, L. Glacier changes and its effect on water resources in the upper reaches of Aksu River, Tien Shan, China, from 1989 to 2016. Arabian Journal of Geosciences. 2022, 15.
4. Liu, Q.; Liu, S.J.C.D. Response of glacier mass balance to climate change in the Tianshan Mountains during the second half of the twentieth century. 2016, 46, 303-316.
5. Braithwaite, R.J.; Hughes, P.D. Regional Geography of Glacier Mass Balance Variability Over Seven Decades 1946–2015. Frontiers in Earth Science. 2020, 8.
6. Duan, K.; Yao, T.; Wang, N.; Liu, H. Numerical simulation of Urumqi Glacier No. 1 in the eastern Tianshan, central Asia from 2005 to 2070. Chinese Science Bulletin. 2012, 57.
7. Xu, C.; Li, Z.; Wang, P.; Anjum, M.N.; Li, H.; Wang, F. Detailed comparison of glaciological and geodetic mass balances for Urumqi Glacier No.1, eastern Tien Shan, China, from 1981 to 2015. Cold Regions Science and Technology. 2018, 155.
8. Guining, Z.; Zhengyong, Z.; Lin, L.; Zhongqin, L.; Puyu, W.; Liping, X. Simulation and construction of the glacier mass balance in the Manas River Basin, Tianshan, China from 2000 to 2016. Journal of Geographical Sciences. 2020, 30.
9. Kenzhebaev, R.; Barandun, M.; Kronenberg, M.; Chen, Y.; Usubaliev, R.; Hoelzle, M. Mass balance observations and reconstruction for Batysh Sook Glacier, Tien Shan, from 2004 to 2016. Cold Regions Science and Technology. 2017, 135.
10. Wang, P.; Li, Z.; Li, H.; Wang, W.; Yao, H. Comparison of glaciological and geodetic mass balance at Urumqi Glacier No. 1, Tian Shan, Central Asia. Global and Planetary Change. 2014, 114.
11. Numerical simulation of Urumqi Glacier No.1 in the eastern Tianshan,central Asia from 2005 to 2070. Chinese Science Bulletin. 2012, 57, 4505-4509.
12. Reeh, N.J.P. Parameterization of melt rate and surface temperature on the Greenland ice sheet. 1991, 5913, 113-128.
13. Jóhannesson, T.; Sigurdsson, O.; Laumann, T.; Kennett, M.J.J.o.G. Degree-day glacier mass-balance modelling with applications to glaciers in Iceland, Norway and Greenland. 2017, 41, 345-358.
14. Yuhuan, C.; Baisheng, Y.; Jie, W.; Youcun, L.. Influence of Degree-Day Factor Variation on the Mass Balance of Glacier No. 1 at the Headwaters of ürümqi River,China. Journal of Earth Science. 2013, 24, 1008-1022.
15. Lihua, W.; Huilin, L.; Lin, W. Application of a Degree-Day Model for Determination of Mass Balance of Urumqi Glacier No. 1, Eastern Tianshan, China. Journal of Earth Science. 2011, 22, 470-481.
16. Baumann, S. Comparison of Glacier Mass Balance Data in the Tien Shan and Pamir, Central Asia. Arctic, Antarctic, and Alpine Research. 2017, 49.
17. Wang, P.; Li, Z.; Li, H.; Yao, H.; Xu, C.; Zhou, P.; Jin, S.; Wang, W. Analyses of recent observations of Urumqi Glacier No. 1, Chinese Tianshan Mountains. Environmental Earth Sciences. 2016, 75.
18. Xu, M.; Wu, H.; Kang, S. Impacts of climate change on the discharge and glacier mass balance of the different glacierized watersheds in the Tianshan Mountains, Central Asia. Hydrological Processes. 2018, 32.

19. Yanjun, C.; Mingjun, Z.; Zhongqin, L.; Yanqiang, W.; Zhuotong, N.; Huilin, L.; Shengjie, W.; Bo, S. Energy balance model of mass balance and its sensitivity to meteorological variability on Urumqi River Glacier No.1 in the Chinese Tien Shan. Scientific reports. 2019, 9.
20. Zhang, Z.; Liu, L.; He, X.; Li, Z.; Wang, P. Evaluation on glaciers ecological services value in the Tianshan Mountains, Northwest China. Journal of Geographical Sciences. 2019, 29.
21. Tongxia, W.; Zhengyong, Z.; Lin, L.; Zhongqin, L.; Puyu, W.; Liping, X.; Guining, Z.; Hao, T.; Ziwei, K.; Hongjin, C., et al. Simulation of the Potential Distribution of the Glacier Based on Maximum Entropy Model in the Tianshan Mountains, China. Water. 2021, 13.
22. Ren, L.; Xue, L.-q.; Liu, Y.-h.; Shi, J.; Han, Q.; Yi, P.-f. Study on Variations in Climatic Variables and Their Influence on Runoff in the Manas River Basin, China. Water. 2017, 9.
23. Zhang, F.; Bai, L.; Li, L.; Wang, Q. Sensitivity of runoff to climatic variability in the northern and southern slopes of the Middle Tianshan Mountains, China. Journal of Arid Land. 2016, 8.
24. Luo, Y. The mass balances modeling and the relationship with meteorological parameters GlaciersinTianshan, Xinjiang, China. Master, Northwest Normal University, 2012.
25. Yong, Z.; Shiyin, L.; Yongjian, L.; Jing, L.; Donghui, SG. Preliminary Study of Mass Balance on the Keqicar BaxiGlacier on the South Slopes of Tianshan Mountains. Journal of Glaciology and Geocryology. 2006, 477-484.
26. Braithwaite, R.J.; Zhang, Y.; Raper, S.J.z.f.g.u.g. Temperature sensitivity of the mass balance of mountain glaciers and ice caps as a climatological characteristic. 2002.
27. Braithwaite, R.J.; Glaciology, O.O.J.J.o. Seasonal variation of ice ablation at the margin of the Greenland ice sheet and its sensitivity to climate change, Qamanrssp sermia, West Greenland. 1993, 39, 267-274.
28. Ersi; Kang; Guodong; Cheng; Yongchao; Lan; Huijun; D, J.J.S.i.C.S. A model for simulating the response of runoff from the mountainous watersheds of inland river basins in the arid area of northwest China to climatic changes. 1999.
29. Wang; Guangjie; Peng; Wenfu. Quantifying spatiotemporal dynamics of vegetation and its differentiation mechanism based on geographical detector. Environmental Science and Pollution Research. 2022.
30. Xingran, C.; Zhongqin, L.; Hui, Z.; Chunhai, X. Vulnerability of glacier change in the Tianshan Mountains region of China. Journal of Geographical Sciences. 2021, 31, 1469-1489.
31. Jinfeng, W.; Chengdong, X. Geodetector: Principle and prospective. Acta Geographica Sinica. 2017, 72, 116-134.
32. Arindam, C.; Chand, S.M.; Sunil, K.D.; Manasi, D. Glacier changes in the Chhombo Chhu Watershed of the Tista basin between 1975 and 2018, the Sikkim Himalaya, India. Earth System Science Data. 2021, 13.
33. Jing, H.; Ninglian, W.; An'an, C.; Xuewen, Y.; Ting, H. Glacier Changes in the Qilian Mountains, Northwest China, between the 1960s and 2015. Water. 2019, 11.
34. Zhang, Q.; Chen, Y.; Li, Z.; Li, Y.; Xiang, Y.; Bian, W. Glacier changes from 1975 to 2016 in the Aksu River Basin, Central Tianshan Mountains. Journal of Geographical Sciences. 2019, 29.
35. Yajuan, C. Junping, Y. A comparison on characteristics of climate change in the north and south of Tianshan Mountain. Journal of Arid Land Resources and Environment. 2011, 25, 92-96, doi:10.13448/j.cnki.jalre.2011.12.032.
36. Hongzheng, P.; Tianding, H.; Peng, C.; Xiangying, L.; Keqin, J. Characteristics of Air Temperature in the Southern and Northern Slopes of Tianshan Mountains. Plateau Meteorology. 2015, 34, 753-761.
37. Zhang, X.; Liu, L.; Zhang, Z.; Kang, Z.; Tian, H.; Wang, T.; Chen, H. Spatial and Temporal Variation Characteristics of Glacier Resources in Xinjiang over the Past 50 Years. 2022, 14, 1057.
38. Wucheng, X.; Zhongqin, L.; Hui, Z.; Mingjun, Z.; Pengbin, L.; Jianxin, M. Spatial-temporal variation of glacier resources in Chinese Tianshan Mountains since 1959. Acta Geographica Sinica. 2017, 72, 1594-1605.

39. Xiaohui, Y.; Jingdong, Z.; Hui, H. Study on glacier mass balance in the Karlik Range, East Tianshan Mountains，1972-2016. Journal of Glaciology and Geocryology. 2019, 41, 1-11.
40. Ninglian, W.; Tandong, Y.; Baiqing, X.; Anan, C.; Weicai, W. Spatiotemporal Pattern, Trend, and Influence of Glacier Change in Tibetan Plateau and Surroundings under Global Warming. Bulletin of Chinese Academy of Sciences. 2019, 34, 1220-1232, doi:10.16418/j.issn.1000-3045.2019.11.005.
41. Puyu, W.; Zhongqin, L.; Huilin, L.; Lihua, W.; Shuang, J.; Ping, Z. Changes of Ice-thickness and Volume for Representative Glaciers in 'Tianshan Mountains in the Past 50 Years. Acta Geographica Sinica. 2012, 67, 929-940.
42. Yanjun, C.; Mingjun, Z; Zhongqin, L.; Shuang, J.; Wenbin, W.; Shengjie, W. Understanding the mass balance characteristics of Qingbingtan Glacier No.72 during the period of 2008-2014. Journal of Glaciology and Geocryology. 2020, 42, 318-331.
43. Chaturvedi, R.K.; Kulkarni, A.; Karyakarte, Y.; Joshi, J.; Bala, G. Glacial mass balance changes in the Karakoram and Himalaya based on CMIP5 multi-model climate projections. Climatic Change. 2014, 123.
44. R, C.R.; Filippo, G.; Csaba, T. Unprecedented heat wave in December 2015 and potential for winter glacier ablation in the eastern Alps. Scientific reports. 2017, 7.
45. Yulan, Z.; Tanguang, G.; Shichang, K.; Donghui, S.; Xi, L. Albedo reduction as an important driver for glacier melting in Tibetan Plateau and its surrounding areas. Earth-Science Reviews. 2021, 220.
46. Yongpeng, G.; Xiaojun, Y.; Shiyin, L.; Miaomiao, Q.; Hongyu, D.; Juan, L.; Dahong, Z. Spatial-temporal variation of glacier resources in the Hexi interior from 1956 to 2017. Journal of Glaciology and Geocryology. 2019, 41, 1313-1325.
47. Wuchao, Y. Runoff characteristics, attribution analysis and futureprediction of the cold and arid Regions: a case study of headwater of the Manas. Master, Northwest A&F University, 2021.
48. Yanlong, G. Changes of Global Climate Landscape Pattern and lts Impact on Surface Water Resource in Qinghai-Tibet Plateau. Doctor, North China Electric Power University, 2021.
49. Zongli, J.; Lei, W.; Zhen, Z.; Shiyin, L.; Yong, Z.; Zhiguang, T.; Junfeng, W.; Danni, H.; Shasha, Z. Surface elevation changes of Yengisogat Glacier between 2000 and 2014. Arid Land Geography. 2020, 43, 12-19.
50. Li, Z.; Shi, X.; Tang, Q.; Zhang, Y.; Gao, H.; Pan, X.; Déry, S.J.; Zhou, P. Partitioning the contributions of glacier melt and precipitation to the 1971–2010 runoff increases in a headwater basin of the Tarim River. Journal of Hydrology. 2020, 583.
51. Megumi, W.; Aki, Y.; Yukiko, H.; Satoshi, W.; Akiko, S.; Shinjiro, K. UNCERTAINTY FROM CLIMATE FORCING OF PROJECTIONS IN GLACIER MELT FOR HIGH MOUNTAIN ASIA. Journal of Japan Society of Civil Engineers, Ser. B1 (Hydraulic Engineering). 2018, 74.
52. Wang, J.; Chen, X.; Liu, J.; Hu, Q. Changes of Precipitation-Runoff Relationship Induced by Climate Variation in a Large Glaciated Basin of the Tibetan Plateau. Journal of Geophysical Research: Atmospheres. 2021, 126.