

## Glacier changes on Muztagh Ata from 1960 to 2023 and analysis of their topographic factors (postprint)

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### Abstract

The glacier changes of Muztag Peak exert an important influence on water resources in southern Xinjiang. Using multi-source remote sensing data from 1960–2023 and deep learning methods, we extracted the glacier area and terminus position changes in the Muztag Peak region, and analyzed the spatial heterogeneity and driving factors of glacier change from the perspectives of individual glacier units and topographic conditions. The results show that: (1) From 1960 to 2023, the glaciers of Muztag Peak exhibited an overall retreating trend, with a glacier area retreat rate of  $0.83 \text{ km}^2 \cdot \text{a}^{-1}$  and a glacier terminus retreat rate of  $2.21 \text{ m} \cdot \text{a}^{-1}$ . Compared with other glaciers in northwestern China, the magnitude of change is relatively small. (2) In terms of intra-glacier spatial differences, the glacier area retreat rate is larger on south-facing and east-facing slopes, and decreases with increasing elevation and slope gradient; in contrast, the glacier terminus retreat rate on the east and west aspects ( $4.42 \text{ m} \cdot \text{a}^{-1}$  and  $4.01 \text{ m} \cdot \text{a}^{-1}$ ) is higher than that on the south and north aspects ( $1.63 \text{ m} \cdot \text{a}^{-1}$  and  $1.45 \text{ m} \cdot \text{a}^{-1}$ ). (3) The spatial differences in glacier area and terminus changes in the Muztag Peak region are mainly controlled by the combined effects of topography and climate. Sun-facing slopes receive more solar radiation, leading to accelerated melting, while low-elevation areas are more prone to retreat due to rising air temperatures. These findings provide a scientific basis for understanding the response mechanisms of glaciers in high-cold mountainous regions to climate change and offer important reference value for water resources management and ecological security assessment in southern Xinjiang.

## Full Text

# Glacier Changes and Topographic Factors of Ulugh Muztagh from 1960 to 2023

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**Abstract:** Changes to glaciers in the Ulugh Muztagh region significantly impact water resources in southern Xinjiang. This study extracted glacier area and terminus changes using multi-source remote sensing data from 1960 to 2023 and deep learning methods. Differences and driving factors were analyzed from the perspectives of glacier units and topographic features. The results show that: (1) Overall, Ulugh Muztagh glaciers retreated from 1960 to 2023, with an average annual area loss of  $0.83 \text{ km}^2$  and a terminus retreat rate of  $2.21 \text{ m} \cdot \text{a}^{-1}$ . (2) In terms of intra-glacier regional differences, the retreat rate of glacier area was higher on south- and east-facing slopes and decreased with increasing elevation and slope. The terminus retreat rate was greater on east- and west-facing slopes ( $4.42 \text{ m} \cdot \text{a}^{-1}$  and  $4.01 \text{ m} \cdot \text{a}^{-1}$ , respectively) than on south- and north-facing slopes ( $1.63 \text{ m} \cdot \text{a}^{-1}$  and  $1.45 \text{ m} \cdot \text{a}^{-1}$ , respectively). (3) The spatial differences in glacier area and terminus changes in the Ulugh Muztagh region are mainly influenced by topography and climate. Sunny slopes receive more solar radiation, accelerating glacier melt, while lower elevations are prone to retreat due to rising temperatures. These findings provide a scientific basis for understanding the mechanisms by which alpine glaciers respond to climate change and offer important references for water resource management and ecological security assessment in southern Xinjiang.

**Keywords:** glacier area; terminus retreat; spatiotemporal variations; topographic factors; climatic elements; Ulugh Muztagh

## 1 Introduction

Under global warming, glaciers worldwide are experiencing accelerated ablation, yet the rate and magnitude of glacier retreat vary significantly across regions. The high, cold mountainous regions of Central Asia are particularly sensitive to climate change, with pronounced glacier melting that not only affects regional water resources but also increases risks of glacial lake outburst floods and landslides. In recent years, catastrophic events such as the outburst floods at Lake

Merzbacher and Shisper Glacier in the Karakoram have highlighted the severe reality of rapid glacial change. Therefore, analyzing and comparing changes in typical glaciers and their driving factors is crucial for understanding glacier response to climate change and for early warning of glacier-related hazards.

While most glacier change studies rely on remote sensing data, differences in data types, acquisition times, mapping methods, and accuracy often lead to inconsistent results for the same glacier. Moreover, glaciers are typically distributed along mountain ridges, and factors such as mountain orientation and aspect can cause the same glacier to span different watersheds, resulting in significant differences in temperature, moisture sources, and topographic conditions that affect glacier development and evolution. Consequently, in-depth study of regional differences in large glacier changes helps deepen understanding of glacier change mechanisms in the high, cold mountainous regions of Central Asia.

Research on glacier changes in western China has made significant progress. Studies show that mountain glaciers in western China have generally accelerated retreat over recent decades, but retreat rates vary substantially among different mountain systems. For example, glaciers in the Altai and Altun Mountains are relatively small and have retreated dramatically, while glaciers in the Tianshan and Himalayas show large internal variations. Meanwhile, glaciers in high-altitude regions such as the Kunlun and Karakoram Mountains have experienced relatively small retreat, with some even showing mass balance near zero or slightly positive. However, glacier changes within the Kunlun and Himalaya ranges exhibit considerable heterogeneity.

Ulugh Muztagh Glacier, located in the central Kunlun Mountains on the northern edge of the Altun Mountain Nature Reserve, is the second largest glacier distribution area in the Kunlun range. Due to its remote location, observational data for this region are scarce. Existing studies primarily rely on remote sensing data to analyze glacier area, mass balance, and surging events. However, area change results for Ulugh Muztagh Glacier have been inconsistent across studies. From a mass balance perspective, different periods show decreasing, increasing, and then decreasing trends. Additionally, both advancing and retreating phenomena coexist in this region, with the tongues of Ulugh Muztagh Glacier and Congliu Glacier currently still advancing. Therefore, obtaining long-term, high-precision glacier change information is essential for revealing change mechanisms and assessing the development potential of glacier water resources.

## 2 Study Area, Data Sources, and Methods

### 2.1 Study Area

The Ulugh Muztagh region is located at the junction of the northern Tibetan Plateau in Xinjiang ( $36^{\circ}16' \sim 36^{\circ}42'N$ ,  $87^{\circ}05' \sim 87^{\circ}39'E$ ) and represents the second largest glacier distribution area in the Kunlun Mountains (Fig. 1). The terrain is characterized by an irregular pyramid shape with a main ridge running

northeast-southwest, reaching a maximum elevation of 6973 m and an average regional elevation of 5557 m. According to the Second Glacier Inventory, the region contains 662.20 km<sup>2</sup> of glaciers. The unique north-south cross-ridge connection forms a substantial compound plateau glacier complex. Although precipitation is relatively low, perennial low temperatures facilitate good glacier development, primarily fed by summer precipitation. Glaciers in the Ulugh Muztagh region are the main water source for surrounding rivers and lakes, with south-facing glacier meltwater feeding alpine lakes such as Yanghu, Xuejinghu, and Achik Kol, while north-facing glacier runoff flows into the Qarqan River system.

## 2.2 Data Sources

To reconstruct the time series of glacier area and terminus changes in Ulugh Muztagh from 1960 to 2023, this study collected multi-source remote sensing data including aerial photogrammetric topographic maps from the 1960s, Landsat series satellite imagery, and Sentinel-2 imagery. To ensure geometric consistency across different periods, all data underwent geographic registration and projection conversion. Glacier boundaries were extracted from multi-temporal Landsat and Sentinel-2 imagery (Table 1), with cloud-free images selected to minimize seasonal snow cover and cloud obstruction effects. The Second Glacier Inventory dataset was referenced for glacier identification and attribute data. Topographic data were derived from the 12.5 m resolution Advanced Land Observing Satellite (ALOS) Global Digital Elevation Model (DEM).

## 2.3 Methods

**2.3.1 Glacier Boundary Extraction and Error Assessment** To ensure comparability of glacier data across different periods, 1:100,000 scale aerial photogrammetric topographic maps from the 1960s were digitized in ArcMap software using 12.5 m resolution ALOS DEM from the same period to improve spatial accuracy. During manual delineation, contemporary glaciological standards were followed, and topographic ridgelines extracted from the DEM were used as auxiliary boundaries to ensure consistency with modern remote sensing datasets.

For Landsat and Sentinel-2 imagery, a DUNet-based semantic segmentation method was employed for automated glacier boundary extraction. This model integrates the advantages of U-Net and deformable convolutional networks, adapting the receptive field according to glacier size and shape, making it particularly suitable for high-precision segmentation of glacier boundaries under complex terrain conditions. The extraction process involved three steps: (1) Sample preparation: 1024  $\times$  1024 pixel images were randomly selected from various geomorphic backgrounds, with preliminary pixel samples and augmented through rotation, mirroring, Gaussian blur, and brightness adjustment before being split into training and testing sets at an 8:2 ratio. (2) Model training and fine-tuning: The DUNet model was trained on the training set and evaluated on the testing set, with parameters

fine-tuned to optimize segmentation accuracy. (3) Prediction and manual revision: The trained model was applied to all Landsat and Sentinel-2 images to automatically extract glacier boundaries. After automated extraction, boundaries were refined through consistency checks and manual revision when necessary, with topographic ridgelines from the ALOS DEM used to ensure accuracy and consistency across time periods. This standardized workflow, combining rigorous preprocessing, advanced semantic segmentation, and topographic-assisted revision, successfully constructed a high-consistency time series of glacier boundaries for Ulugh Muztagh from 1960 to 2023.

To assess the geometric accuracy of extracted glacier boundaries, this study adopted the error evaluation method proposed by Bolch et al. [36], using  $\pm 15$  m as the uncertain area for Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+), and Operational Land Imager (OLI) images, and  $\pm 12.5$  m for Sentinel-2 imagery.

**2.3.2 Quantitative Calculation of Glacier Tongue Terminus Retreat Rate** Due to the irregular shape of glacier termini and varying retreat rates among different glaciers, this study employed the principal axis parallel line method to quantify glacier terminus changes. Specifically, multi-segment lines parallel to the longest axis were used to cut the glacier terminus, with the average change across all segments representing the terminus change value. This method effectively reduces measurement errors caused by irregular glacier shapes.

The glacier terminus retreat rate ( $G$ ) was calculated using the following formula:

$$G = \frac{\sum_{i=1}^n \frac{L_i^{t-1} - L_i^t}{\Delta t}}{n}$$

where  $G$  is the terminus retreat rate ( $\text{m} \cdot \text{a}^{-1}$ ),  $L_i^{t-1}$  and  $L_i^t$  are the lengths of the  $i$ -th parallel line segment measured on images from time  $t-1$  and  $t$ , respectively;  $\Delta t$  is the time interval between images; and  $n$  is the number of parallel line segments.

**2.3.3 Analysis of Relationships Between Topographic Factors and Glacier Retreat** To analyze the relationships between glacier area change, terminus retreat characteristics, and glacier scale and topographic factors (elevation, slope, aspect), the following procedure was adopted: (1) Data preparation and variable extraction: Using the extracted glacier boundaries and ALOS DEM data, ArcGIS tools were used to calculate primary topographic characteristics for each glacier unit, including mean elevation, maximum elevation, minimum elevation, mean slope, and aspect distribution. To represent the mean azimuth of aspect, the sine and cosine of angles were used to quantify differences in north-south and east-west directions. All data were registered and corrected to ensure accuracy. (2) Correlation analysis: Pearson correlation coefficients were used to

quantify relationships between topographic factors and glacier area change and terminus retreat. Statistical significance was determined using P-values, with  $P < 0.05$  considered significant.

### 3 Results and Analysis

#### 3.1 Glacier Area Changes

From 1960 to 2023, the total glacier area in Ulugh Muztagh decreased from  $703.51 \pm 6.97 \text{ km}^2$  to  $651.50 \pm 5.83 \text{ km}^2$ , representing a total reduction of  $52.01 \text{ km}^2$  (7.39% of the 1960 total area). The retreat rate varied significantly across different periods: 1960-1990 showed a slow retreat with an average annual rate of  $0.06\% \cdot \text{a}^{-1}$ ; 1990-2000 experienced accelerated retreat at  $0.14\% \cdot \text{a}^{-1}$ ; 2000-2015 showed a slowdown with rates of  $0.06\% \cdot \text{a}^{-1}$ ; and 2015-2023 saw significant acceleration to  $0.23\% \cdot \text{a}^{-1}$ . Overall, glaciers in the region have shown a continuous retreat trend, with the rate markedly accelerating in recent years.

In terms of glacier size and spatial distribution (Fig. 3), glacier area is concentrated in the  $>5 \text{ km}^2$  range (approximately 85.37%), with north- and east-facing glaciers having larger areas than south- and west-facing ones. This is primarily because north- and east-facing glaciers are more extensive and have larger initial areas.

Regarding area loss and retreat rates (Fig. 4), significant differences exist across aspects and slopes. North, southwest, south, and southeast-facing glaciers showed larger absolute area losses of  $7.16 \text{ km}^2$ ,  $7.67 \text{ km}^2$ ,  $7.56 \text{ km}^2$ , and  $7.28 \text{ km}^2$ , respectively. However, higher area retreat rates were concentrated on southwest, south, southeast, and east-facing slopes at 7.32%, 8.08%, 7.49%, and 7.02%, respectively. In terms of slope, absolute area loss is concentrated in the  $5^\circ$ - $15^\circ$  range, accounting for 56.33% of total retreat area, while retreat rates are higher in the  $0^\circ$ - $25^\circ$  range, peaking at  $5^\circ$ - $15^\circ$ . Glacier area distribution across elevation shows a near-normal distribution, concentrated in the 5300-6000 m range (85.37% of total area), with area retreat primarily occurring in the 5000-5400 m zone. Retreat rates decrease significantly with increasing elevation, with higher rates observed in the 5200-5700 m interval, which accounts for 60.68% of total retreat area.

#### 3.2 Regional Characteristics of Glacier Tongue Terminus Changes

To explore regional differences in glacier tongue retreat, this study selected 84 representative glaciers with distinct terminus features. The results show significant spatial heterogeneity in terminus changes (Fig. 5). While most glaciers retreated, two advanced: the Ulugh Muztagh Glacier on the north slope of the southwestern corner and the Congliu Glacier on the south slope, whose termini advanced 218.55 m and 226.54 m along their main axes, respectively, with average advance rates of  $3.47 \text{ m} \cdot \text{a}^{-1}$  and  $3.60 \text{ m} \cdot \text{a}^{-1}$ .

Further analysis of the influence of glacier size, aspect, slope, and elevation on

terminus retreat rates revealed complex relationships (Fig. 6). For example, in the 5100–5300 m elevation band, terminus retreat rates increased from  $0.33 \text{ m} \cdot \text{a}^{-1}$  to  $7.89 \text{ m} \cdot \text{a}^{-1}$ , while in the 5300–5500 m band, rates stabilized between  $1.03$ – $2.46 \text{ m} \cdot \text{a}^{-1}$ . In the 5500–5700 m band, retreat rates decreased to  $0.27 \text{ m} \cdot \text{a}^{-1}$ . Regarding glacier size, all size classes except the  $1$ – $2 \text{ km}^2$  and  $20$ – $50 \text{ km}^2$  ranges showed that larger glaciers had higher terminus retreat rates, indicating that large glaciers retreat more significantly at their termini. Topographically, east- and west-facing glaciers showed markedly higher terminus retreat rates than north- and south-facing glaciers, with west-facing glaciers retreating fastest at  $4.42 \text{ m} \cdot \text{a}^{-1}$ . Additionally, terminus retreat rates decreased with increasing slope. Analysis of terminus elevation distribution showed that glacier termini are concentrated in the 5100–5600 m range, with retreat rate fluctuations increasing as elevation decreases.

### 3.3 Analysis of Topographic Driving Factors of Glacier Changes

Using 84 glaciers as samples, correlation analysis was conducted between topographic factors (size, minimum elevation, maximum elevation, mean elevation, mean slope, and aspect) and glacier retreat. The results (Table 4) show that for absolute area loss, glacier size ( $r = 0.58$ ,  $P < 0.001$ ) and maximum elevation ( $r = 0.69$ ,  $P < 0.001$ ) are significantly positively correlated, indicating that larger glaciers and those with higher maximum elevations experienced greater absolute area losses. Mean slope showed a significant negative correlation with area loss ( $r = -0.27$ ,  $P < 0.01$ ), suggesting that steeper glaciers experienced smaller area losses. This is attributed to the irregular pyramid shape of Ulugh Muztagh, where upper slopes are steeper and retreat begins from lower termini, resulting in relatively lower area loss on high-slope regions.

For glacier area retreat rates, maximum elevation ( $r = -0.31$ ,  $P < 0.01$ ), mean elevation ( $r = -0.28$ ,  $P < 0.01$ ), and size ( $r = -0.34$ ,  $P < 0.001$ ) all showed significant negative correlations, indicating that small, low-elevation glaciers are more prone to high proportional area loss. Mean slope showed a significant positive correlation with area retreat rate ( $r = 0.29$ ,  $P < 0.01$ ), meaning steeper glaciers have higher area retreat rates.

Analysis of terminus retreat rates revealed different topographic driving effects: glacier size ( $r = 0.37$ ,  $P < 0.01$ ), maximum elevation ( $r = 0.51$ ,  $P < 0.001$ ), and mean elevation ( $r = 0.28$ ,  $P < 0.01$ ) were significantly positively correlated with terminus retreat rate, indicating that larger glaciers and those at higher elevations retreat faster at their termini.

Overall, topographic features including glacier size, elevation, slope, and aspect exhibit complex, multi-layered driving effects on glacier retreat. Large, high-elevation glaciers show more obvious absolute area losses, but not necessarily higher retreat rates. However, larger glaciers at higher elevations tend to accelerate terminus retreat.

## 4 Discussion

### 4.1 Regional Differences and Topographic Modulation of Glacier Changes in Ulugh Muztagh

Previous studies have shown that under global warming, glacier changes exhibit significant regional heterogeneity, primarily controlled by combined climate and topographic factors. Compared with other glacier regions in western China, Ulugh Muztagh shows relatively small glacier area change rates but significant spatial heterogeneity. This heterogeneity is not only reflected in the direct effects of traditional topographic factors such as aspect and elevation but also demonstrates the regulating and buffering effects of terrain on glacier retreat processes under climate change.

The ridge line of Ulugh Muztagh runs northeast-southwest, with south- and east-facing slopes receiving strong solar radiation in summer, increasing surface energy input and accelerating glacier melt. In contrast, north- and west-facing slopes are shaded, receiving less solar radiation. Moreover, high-elevation areas have lower temperatures and are less sensitive to temperature increases, resulting in slower glacier retreat. Regional moisture conditions are also influenced by topography. The Kunlun Mountains serve as an important topographic barrier on the northern edge of the Tibetan Plateau, significantly intercepting moisture transported by westerly winds. Remote sensing and meteorological data analyses show that westerly moisture forms orographic precipitation on windward slopes (west and north), while leeward slopes (east and south) become relatively dry due to subsidence. Insufficient precipitation further exacerbates glacier area retreat on south- and east-facing slopes.

Although aspect and precipitation differences explain some spatial heterogeneity, the overall change trend is closely related to topographic modulation capacity. The average elevation of Ulugh Muztagh glaciers is 5557 m, with some glacier termini retreating to sheltered terrain above 6000 m. This high elevation reduces the response of glaciers to temperature increases, providing a “protective” effect. Remote sensing monitoring shows that although terminus retreat rates are high on west- and east-facing slopes ( $4.42 \text{ m} \cdot \text{a}^{-1}$  and  $4.01 \text{ m} \cdot \text{a}^{-1}$ , respectively), retreat occurs mainly in low-elevation zones, while high-elevation sections remain stable. This indicates that while glacier retreat is a direct response to climate change, topographic factors gradually become key variables regulating the intensity of this response.

Compared with other glacier regions in western China, Ulugh Muztagh has lower temperatures (annual average  $-11.5^{\circ}\text{C}$ ) and moderate precipitation (500–1200 mm), with small interannual temperature fluctuations and low summer temperature variation (approximately  $8.0^{\circ}\text{C}$ ). These low-temperature and stable precipitation conditions help maintain relatively stable glaciers (Table 5). The region’s glacier area retreat rate of  $0.12\% \cdot \text{a}^{-1}$  is significantly lower than that of Yiliha Bierga Mountain in the Tianshan range ( $0.75\% \cdot \text{a}^{-1}$ ) and Dongkemadi in the Tanggula Mountains ( $0.68\% \cdot \text{a}^{-1}$ ), indicating that high-altitude, large-scale

glacier regions are more stable under climate warming.

In summary, glacier changes in Ulugh Muztagh are not simply the superposition of climate and topographic factors but represent a complex coupling of both. Climate change constitutes the primary driver, while topographic factors gradually exert regulating and buffering effects, especially after glaciers have significantly retreated to higher elevation zones. The “protective” space provided by terrain is crucial for glacier stability.

## 4.2 Comparative Analysis of Typical Glacier Changes in Western China

Climate warming is the main driver of global glacier retreat, but the speed and intensity of glacier changes in different geographic units are regulated by multiple factors, particularly moisture supply and topographic conditions. In western China, glaciers in different mountain systems show differentiated response mechanisms under similar climate backgrounds, reflecting significant regional characteristics. In the Ulugh Muztagh region, although the average annual temperature has generally increased over the past 60 years, the high altitude maintains low annual average temperatures ( $-8.0$  to  $4.1^{\circ}\text{C}$ ), with slight precipitation increases and small summer temperature variation (approximately  $8.0^{\circ}\text{C}$ ). Compared with the Altai Mountains (annual average temperature  $-3.0^{\circ}\text{C}$ , precipitation 75–700 mm) and Tianshan Mountains (annual average temperature  $-8.0$  to  $4.1^{\circ}\text{C}$ , precipitation 500–1200 mm), Ulugh Muztagh’s low-temperature and stable moisture conditions contribute to slower retreat.

Overall, Ulugh Muztagh exhibits three key characteristics: (1) Extremely high elevation, with the main peak reaching 6973 m and average glacier distribution at 5557 m, placing glaciers in the upper troposphere where they are less responsive to climate change; (2) Small temperature fluctuations with lower annual average temperatures and reduced summer temperature variation, creating a stable low-temperature environment conducive to slow ablation; (3) Large glacier size and rich ice reserves provide strong thermal inertia, resulting in a lagged and less dramatic response to climate change.

Integrated climate and topographic analysis reveals that the slow retreat of Ulugh Muztagh glaciers is not merely a “rate” phenomenon but reflects a “weak response” mechanism under long-term climate warming. Against the backdrop of widespread global glacier retreat, the relative stability of Ulugh Muztagh glaciers highlights the critical role of high-altitude, large-scale glacier regions in modulating climate warming impacts.

## 5 Conclusions

- (1) From 1960 to 2023, Ulugh Muztagh glaciers showed an overall retreat trend, with a total area loss of  $52.01 \text{ km}^2$  and an average annual retreat rate of  $0.12\% \cdot \text{a}^{-1}$ . Although the termini of Congliu Glacier and Ulugh

Muztagh Glacier showed slight local advances, most glacier termini exhibited obvious retreat, with an average rate of  $2.21 \text{ m} \cdot \text{a}^{-1}$ .

- (2) Glacier retreat in Ulugh Muztagh shows significant spatial heterogeneity. The most pronounced retreat occurred on southwest-, south-, southeast-, and east-facing slopes, with retreat zones mainly distributed in the  $5^{\circ}$ – $15^{\circ}$  slope range. Area loss is significantly negatively correlated with slope, and area loss decreases with increasing elevation, concentrating in the 5200–5700 m elevation band. Terminus retreat rates increase with glacier size, are higher on east- and west-facing slopes than on north- and south-facing slopes, decrease with increasing slope, and increase with decreasing elevation.
- (3) Compared with other glaciers in western China, Ulugh Muztagh glaciers are retreating relatively slowly, mainly due to low regional temperatures and relatively stable moisture supply. However, local topography and uneven moisture distribution still cause obvious spatial heterogeneity in glacier changes. Although climate warming is the primary driver of glacier retreat, topographic factors—particularly the “protective” effect of high elevation—play a crucial role in modulating climate warming impacts.

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