Postprint: Movement Characteristics of Major Glaciers on the North Slope of K2, Karakoram Mountains

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Abstract

Surface velocities of 42 glaciers on the northern slope of the Karakoram Mountains were extracted using ITS_{LIVE} and Landsat data. By combining terminus motion with surface motion characteristics, the spatiotemporal variations in surface velocity of glaciers with different motion types were analyzed and compared. The results show that: (1) During 1989-2018, among the 42 glaciers in the study area, there were 16 stable glaciers, 6 advancing glaciers, 1 retreating glacier, and 19 surging glaciers. Spatially, the velocity distribution conforms to the general principles of glacier motion, with distinct high-value areas identifiable in the accumulation zone and upper tongue, which mostly occur in the main trunk or tributaries of surging glaciers, with velocity magnitudes generally exceeding 100.00 m · a-1; for instance, the maximum velocity in the southern tributary of the Yinsugaiti Glacier can reach 358.33 m · a- 1. (2) The distribution of glacier velocity is closely related to topographic factors. Velocity reaches its maximum between elevations of 4600~ 5000 m (54.55 m · a-1), which is more than 10 times the velocity at the glacier terminus; the average velocity is highest for the 42 glaciers distributed on slopes of 0~5°, and velocity gradually decreases as slope increases; glaciers facing east have the highest velocity, while those facing southwest have the lowest velocity. (3) The interannual variation in velocity of stable glaciers is relatively stable, with velocity values at the same location being relatively consistent across different years; whereas for advancing and retreating glaciers, interannual velocity fluctuations are both relatively large; for surging glaciers, interannual velocity variations differ across different locations. For surging glaciers with advancing termini, surface velocity changes are minor, yet terminus change velocity can exceed 100.00 m · a-1, even reaching 500.00 m · a-1. (4) Glaciers with greater length and larger area are more prone to surging. Climate, avalanches, and topography are also the main factors influencing variations in glacier motion velocity.

Full Text

Characteristics of Major Glacial Movements on the Northern Slope of K2, Karakoram

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Abstract

The surface velocity of 42 glaciers on the northern slope of K2 (Mount Qogir), Karakoram was extracted from ITS_{LIVE} and Landsat data. Combined with data regarding the characteristics of end and surface movements, the spatial and temporal variations of the surface velocity of glaciers with different movement types were analyzed and compared. The results show that: (1) From 1989 to 2018, among the 42 glaciers in the study area, we observed 16 stable, 6 advancing, 1 retreating, and 19 surging glaciers. The velocity distribution in space is consistent with the general principle of glacier movement, and obvious high-value areas can be found in the accumulation area and upper region of the glacier tongue; these areas are mostly in the trunk or branch of the active glacier, and the velocity is generally >100.00 $m \cdot a^{-1}$. For example, in the southern branch of the Yengisogat glacier, the maximum velocity can reach 358.33 $m \cdot a^{-1}$. (2) The glacier velocity distribution is closely related to topographical factors. The maximum flow velocity (54.55 $m \cdot a^{-1}$) is between 4600 m and 5000 m, which is >10 times that of the end of the glacier. The average velocity of the 42 glaciers in the slope angle range of 0° to 5° is the highest, and the velocity decreases with the increase of the slope angle. Glaciers flowing toward the east have the greatest flow rate, and those that flow toward the southwest have the smallest. (3) The interannual variation of the velocity of the stable glacier is small, and the velocity values at the same location are consistent across different years. For advancing and retreating glaciers, the fluctuation in interannual velocity is large. The annual velocity variation of the surging glacier is found to be location dependent. The surface velocity of the glacier with a moving tip shows little change, but the change velocity of the glacier tip can be >100.00 $m \cdot a^{-1}$ and even up to 500.00 $m \cdot a^{-1}$. (4) Glaciers with longer lengths and larger areas are prone to surge. Climate, avalanches, and topography also play a major role in determining glacier speed.

Keywords: glacier; northern slope of the Karakoram Mountains; ITS_{LIVE} data; Landsat data; surface velocity; spatial and temporal variations

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1. Study Area Overview

The northern slope of the Karakoram Mountains is roughly located at 35°31 –36°49 N, 75°35 –77°00 E. According to China' s Second Glacier Inventory, the glacier code for this region is "5Y654," with a watershed area of 5730 km^2. The modern glaciers in this area develop on mountain ranges with an average elevation above 7000-8000 m, with the main peak, K2 (Mount Qogir), reaching 8611 m. The highest glacier is the K2 Glacier at 8569 m, while the remaining glaciers are at 3800-8600 m. The climate on the northern slope of the Karakoram Mountains is influenced by the Asian monsoon, with 70% of precipitation contributed by summer rainfall. In winter, the region is controlled by the westerly circulation, and 30% of snowfall occurs at high altitudes. Annual precipitation in the valley is less than 100 mm, but it gradually increases with altitude. The equilibrium line is roughly at 5100-5400 m, and the summer average temperature is 1.2-3.0 °C, with annual precipitation between 100-500 mm. Glacier mass is mainly supplied by avalanches, which provide 60% of the glacier material. Based on glacier scale, size, and morphology, 42 glaciers were selected as the study area [Figure 1: see original paper].

2. Data Sources and Methods

2.1 Data Sources

The remote sensing imagery data were obtained from the Geospatial Data Cloud website (http://www.gscloud.cn/), with image path/row numbers of 148/35. The data consist of Landsat 5 TM, Landsat 7 ETM+, and Landsat 8 OLI Level L1T data . All data have undergone geometric correction, radiometric correction, and terrain correction based on a digital surface model. Due to the high altitude, abundant snowfall, frequent cloud and fog cover, and debris-covered surfaces in the study area, image interpretation is difficult. Therefore, this study selected summer and autumn images with minimal cloud, snow, and fog cover whenever possible.

The ITS_{LIVE} (The Inter-mission Time Series of Land Ice Velocity and Elevation) product is a regional compilation of annual average surface velocities of major glaciers, spanning 1985-2018. The data can be downloaded from https://its-live.jpl.nasa.gov and represent part of the "Making Earth System Data Records for Use in Research Environments" (MEaSUREs) program. The surface velocities were derived from Landsat images using the automated crevasse feature tracking processing chain method described by Gardner et al. The data resolution is 240 m. This study used the 1989-2018 annual velocity data to investigate glacier surface motion.

Additionally, the Digital Elevation Model (DEM) data were obtained from the ASTER GDEM dataset on the Geospatial Data Cloud (http://www.gscloud.cn/), with a resolution of 30 m. This dataset was primarily used to extract topographic parameters (elevation, slope, aspect, etc.) for the study area. The reliability of this data has been studied by Wang et al. and Zhang et al., who successfully applied it to research on glaciers in the Himalaya and western Karakoram regions. This study also utilized the Second Glacier Inventory data and Chinese administrative district vector data.

2.2 Methods

2.2.1 Glacier Boundary Extraction and Accuracy Assessment Many computer processing software packages provide various automatic or semi-automatic methods for extracting glacier boundaries, but these methods are still limited in terms of accuracy for large-scale applications. Long-term field measurements over extensive areas have been difficult to conduct. Furthermore, factors such as image registration, cloud and snow quality, smooth ice surfaces, debris-covered ice identification, image restoration, and uncertainty in glacier boundary extraction lead to poor correlation in displacement calculations between different time intervals, affecting estimation accuracy. Stationary non-glacier areas such as mountain peaks can be used as a benchmark to assess estimation accuracy.

Therefore, this study used 2018 as an example to conduct accuracy analysis of glacier surface motion monitoring results using non-glacier area residual displacement, based on the fundamental principles of remote sensing glacier motion estimation. The detailed formula is as follows:

The error in glacier area caused by image spatial resolution ( ) can be calculated, where A represents half a pixel size, and N is the perimeter of the glacier outline. The results show that the sum of is 39.27 km^2, accounting for 0.7% of the total area in 2018. The precision of glacier boundaries in other years is also 0.7%, meeting the research requirements.

The error of offset in non-glacier areas (MED_{off}) is the average offset in non-glacier areas, and SE_{off} is the standard error of offset in non-glacier areas. The specific calculation formula is as follows:

SE = STDV/√N_{eff}

where STDV is the standard deviation of the offset in non-glacier areas, and N_{eff} is the number of spatially uncorrelated pixels, calculated as:

N_{eff} = N_{total} / (D_{total}/PS)

where N_{total} is the total number of pixels in non-glacier areas, PS is the pixel resolution (m), and D_{total} is the maximum distance of spatial correlation, which is generally 10 times the pixel resolution. The resulting error of offset in non-glacier areas is 1.413 $m \cdot a^{-1}$, far smaller than the glacier velocity observation values.

2.2.3 Glacier Type Identification Glaciers on the northern slope of the Karakoram are covered by debris, making glacier boundary identification a major challenge. The high altitude and treacherous terrain of Karakoram glaciers, combined with natural conditions, make precise experimental data comparison and validation difficult. However, a series of Landsat images and glacier inventory data can be used to map glacier termini to determine whether glaciers are advancing, stable, or retreating.

Following the definition proposed by Rankl et al., a standard of 3 pixels was used to determine glacier terminus advance. When the glacier terminus advances more than 3 pixels, it is classified as an advancing glacier; when it retreats more than 3 pixels, it is a retreating glacier; otherwise, it is a stable glacier. For surging glacier identification, criteria include terminus changes, surface velocity, surface features (such as crevasses, obvious medial moraine folds on the ice surface, and broken ice surfaces), and terminus thickening. Generally, surging glacier ice flow velocity exceeds that of quiescent glaciers, often causing sudden terminus advance and glacier upper region thinning. Currently, there is no clear definition for specifically distinguishing surging from non-surging glaciers, and there are certain differences between surging and advancing glaciers. Generally, advancing glaciers with terminus velocity >100.00 $m \cdot a^{-1}$ and surface velocity >100.00 $m \cdot a^{-1}$ can be classified as surging. Glacier terminus velocity can be obtained from length changes during the advance period, requiring the extraction of the glacier centerline (the length of the glacier centerline equals glacier length). The glacier centerline can be semi-automatically extracted in ArcGIS based on glacier boundaries and DEM.

3. Results

3.1 Glacier Classification Results

Based on Landsat remote sensing imagery from 1989 to 2018, glacier terminus changes were used to identify 6 advancing glaciers, 1 retreating glacier, 16 stable glaciers, and 19 surging glaciers [Figure 2: see original paper]. During this period, there were still 6 glaciers that had not stopped advancing. The terminus advance velocity was >100.00 $m \cdot a^{-1}$ for 6 glaciers; >200.00 $m \cdot a^{-1}$ for 3 glaciers; and >300.00 $m \cdot a^{-1}$ for 2 glaciers. The advance period was as short as 3 years, with advances mainly concentrated in recent years. Surging glaciers were distributed among advancing, retreating, and stable glaciers. According to glacier surface features and velocity changes, 19 surging glaciers were identified. Among them, surging glaciers with advancing termini were mostly medium-sized glaciers.

3.2 Characteristics of Glacier Surface Movement Velocity

3.2.1 Spatial Distribution Characteristics of Glacier Surface Velocity Based on ITS_{LIVE} data from the US Snow and Ice Center, full-range velocity estimates were made for 42 glaciers on the northern slope of the Karakoram, obtaining the spatial distribution of velocity from 1989 to 2018 [Figure 3: see original paper]. Taking 2018 as an example, the movement characteristics of glaciers in different states were analyzed. The study found that surging glacier velocities ranged from 1.11-9.04 $m \cdot a^{-1}$, with an average of 14.62 $m \cdot a^{-1}$; advancing glacier velocities ranged from 1.38-38.8 $m \cdot a^{-1}$, with an average of 4.32 $m \cdot a^{-1}$; stable glacier velocities ranged from 0.64-7.9 $m \cdot a^{-1}$, with an average of 3.54 $m \cdot a^{-1}$; and retreating glacier velocity was 3.21 $m \cdot a^{-1}$. Clearly, surging glacier velocities are greater than those of other glacier types.

Spatially, the velocity distribution is consistent with the general principle of glacier movement, with obvious high-value areas found in the accumulation area and upper tongue region. These areas mostly appear in the trunk or branches of surging glaciers, with velocities generally >100.00 $m \cdot a^{-1}$. For example, in the southern branch of the Yengisogat glacier, the maximum velocity can reach 358.33 $m \cdot a^{-1}$. The single glacier with the largest average velocity distribution is Glacier No. 5 (38.80 $m \cdot a^{-1}$), and the smallest is Glacier No. 37 (0.64 $m \cdot a^{-1}$).

Glacier velocity spatial distribution is closely related to elevation. The study area glaciers are at 3800–8600 m. When elevation is segmented every 400 m, the average glacier velocity in different elevation intervals in 2018 shows that velocity first increases and then decreases with elevation [Figure 4: see original paper]. Between 3800–4200 m, glacier velocity is 1.58 $m \cdot a^{-1}$. At 4600–5000 m, velocity reaches its maximum (54.55 $m \cdot a^{-1}$), which is >10 times that of the glacier terminus velocity. After 5000 m, velocity gradually decreases, and above 7000 m, glacier movement is slowest.

Glacier movement is also related to slope and aspect. Slope distribution shows that the average velocity of the 42 glaciers is highest in the 0°–5° slope range, and velocity gradually decreases as slope increases. This is similar to the research results of Sam et al. and Zhang et al., possibly because small slopes facilitate glacier area accumulation, fast material exchange, large gravitational components, and rapid downward ice flow. East-facing glaciers have the highest velocity; for example, the east-facing Yengisogat glacier has an average velocity of 21.18 $m \cdot a^{-1}$, while southwest-facing glaciers have the smallest velocity (17.02 $m \cdot a^{-1}$).

3.2.2 Interannual Variation Characteristics of Glacier Surface Velocity Based on the glacier classification above, the interannual variation characteristics of different glacier types were studied. The 16 stable glaciers in the study area showed no obvious terminus advance or surface feature changes. In the 30-year streamline velocity profiles [Figure 5: see original paper], except for slight fluctuations in Glacier No. 5, the other 15 glaciers showed relatively stable interannual changes.

This study identified 6 advancing glaciers (Nos. 12, 14, 29, 30, 31, 37). Their profiles [Figure 6: see original paper] show large interannual velocity variations, with fluctuation amplitudes of 0–30.00 $m \cdot a^{-1}$, presenting an overall unstable state. For example, Glacier No. 12 had the maximum advance distance before 2000, totaling 71.80 $m \cdot a^{-1}$. Glacier No. 14 maintained consistent velocity before 2000. Glacier No. 29 showed large interannual variations 10,000–20,000 m from the top, with surges occurring in 2000 and 2015, when peak velocities reached 320.00 $m \cdot a^{-1}$, while velocities in other years were <100.00 $m \cdot a^{-1}$. Glacier No. 30 had large interannual variations in the accumulation area, with minimum velocity in 2015. Glacier No. 31 showed large interannual variations 5,000–15,000 m from the top, advancing in 2000 with a velocity of 94.82 $m \cdot$

a^{-1}. Glacier No. 37 had velocities >100.00 $m \cdot a^{-1}$ at 7,500–12,000 m from the top, with the maximum advance distance in 2000, indicating at least one surge event. Different glaciers show different interannual velocity variations at different locations.

One retreating glacier (No. 12) was identified [Figure 8: see original paper], showing velocity fluctuations with amplitudes of 0–12.00 $m \cdot a^{-1}$, overall unstable. The velocity variation is complex, with stable interannual changes from 25,000 m to the terminus, and consistent spatiotemporal velocity variations across different years.

Surging glaciers exhibit two behavioral characteristics: those without terminus advance and those with terminus advance. Some glaciers with stable termini show obvious surging in the accumulation or ablation area [FIGURE:9, FIGURE:10]. For example, Glacier No. 0 surged in 2000 and 2015 at 5,000–15,000 m from the top. Glacier No. 2 surged in 2000 and 2015 at 15,000–25,000 m from the top. Glacier No. 5 had small interannual variations. Glacier No. 7 showed large interannual variations, but peak velocity locations were roughly the same as previous years. Glaciers Nos. 9 and 10 had velocities >100.00 $m \cdot a^{-1}$ at 1,000–2,000 m in the ablation area, with interannual differences showing 2018 velocities greater than other years. Other surging glaciers showed small interannual streamline velocity variations, fluctuating between 0–20.00 $m \cdot a^{-1}$, presenting overall instability. Although these glaciers have small surface velocities, their terminus movement velocities are large, with advances of several hundred meters [Figure 11: see original paper]. For example, typical surging glacier No. 0 started surging in 2000, ended in 2015, with a surge period of 15 years, and still showed advancing trends afterward. Glacier No. 2 started surging in 2000, ended in 2015, with a surge period of 15 years, and peak velocity appeared in 2015 at 586.84 $m \cdot a^{-1}$.

4. Discussion

4.1 Glacier Scale and Velocity

Based on the study by Xu et al., we found that glacier velocities in the study area show an increasing trend from 1989 to 2018, which is closely related to increased precipitation and temperature. Research shows that glaciers with areas of 1.71–359.05 km^2 were studied. Surging glaciers mainly occur in glaciers >100 km^2, while stable glaciers are concentrated in glaciers of 2.0–5.0 km^2. There are 6 glaciers with areas of 50–100 km^2, with average velocities of 32.82 $m \cdot a^{-1}$ and 16.95 $m \cdot a^{-1}$; 19 glaciers with areas of 2–50 km^2 have average velocities of 38.80 $m \cdot a^{-1}$, 21.18 $m \cdot a^{-1}$, 25.30 $m \cdot a^{-1}$, and 13.73 $m \cdot a^{-1}$. All surging glacier velocities are greater than those of stable glaciers <50 km^2. Surging glacier lengths are generally greater than other glaciers, meaning glacier surging is more likely to occur in longer glaciers, and surging glacier velocities are greater than stable glacier velocities. Glacier scale has a certain relationship with surface velocity. Large-area glaciers have large accumulation areas with abundant glacier material, promoting forward glacier movement. Therefore, large-area glaciers have higher velocities.

4.2 Climate Control on Glacier Velocity

Jing et al. conducted path analysis on factors affecting glacier movement, including glacier morphology, mass balance, and climate conditions, finding that these factors interact with each other. Glacier morphology directly affects glacier movement speed, while climate factors are important indirect factors that affect mass balance through climate variations, thereby acting on glacier morphology and a series of internal ice structures and stresses that influence glacier movement speed. Different geographical locations and different glaciers have different factors affecting movement speed. Climate factors are the controlling factor, and climate change controls the state of glacier movement.

The geographical location of the northern slope of the Karakoram Mountains is special, influenced by the westerly circulation and the Indian Ocean southwest monsoon, with large amounts of precipitation in winter and summer, which has an important impact on glacier mass accumulation. Although the overall trend is the same, there are differences in variation amplitude. Glacier development conditions affect glacier development and stability. If these stable and balanced development conditions are destroyed, glacier instability is very likely to occur. Therefore, climate change differences in the Karakoram Mountains are the dominant factor causing glacier instability and imbalance in some areas, leading to advances or surges. Glacier movement is controlled by climate, and the most intuitive phenomenon is the seasonal variation of glacier velocity. When precipitation increases, glacier accumulation and thickness increase, promoting glacier movement. When temperature rises, glacier meltwater increases, promoting basal sliding and affecting glacier velocity.

4.3 Glacier Surge Mechanism

Glacier surging is a complex activity, and there is no unified explanation for its mechanism. Existing studies have different views on the causes of Karakoram glacier surging, believing that Karakoram glacier surging is controlled by thermodynamic and hydrological conditions. Jing et al. pointed out that climate factors are the controlling factor, and climate change controls the state of glacier movement. Rankl and Quincey' s research results show that there are many surging glaciers in the Karakoram Mountains, and these glaciers themselves can cause changes in local glacier conditions. Glacier surging may also be the combined effect of rock compression inside or at the bottom of the glacier and temperature changes in the ice caused by hydrological conditions. When the ice surface slope is large, cracking occurs, rolling down and causing the entire ice body to become unstable, thus rapidly sliding down and increasing ice flow velocity, resulting in surging.

5. Conclusions

Based on ITS_{LIVE} and Landsat data, this study extracted the surface velocity of 42 glaciers in the study area and combined terminus movement with surface movement characteristics to compare and analyze the spatial and temporal variations of surface velocity of different movement types. The following conclusions were obtained:

(1) From 1989 to 2018, among the 42 glaciers in the study area, there were 16 stable glaciers, 6 advancing glaciers, 1 retreating glacier, and 19 surging glaciers. During this period, 6 glaciers had not stopped advancing. There were 6 glaciers with terminus advance velocity >100.00 m · a^{-1}, 3 glaciers >200.00 m · a^{-1}, and 2 glaciers >300.00 m · a^{-1}. The advance period was as short as 3 years, with advances mainly concentrated in recent years.

(2) Spatially, the velocity distribution is consistent with the general principle of glacier movement. Obvious high-value areas can be found in the accumulation area and upper tongue region, mostly in the trunk or branches of surging glaciers, with velocities generally >100.00 m · a^{-1}. For example, in the southern branch of the Yengisogat glacier, the maximum velocity can reach 358.33 m · a^{-1}. The glacier with the largest single-glacier average velocity distribution is No. 5 (38.80 m · a^{-1}), and the smallest is No. 37 (0.64 m · a^{-1}).

(3) Overall, glacier velocity is closely related to topographical factors. The maximum velocity (54.55 m · a^{-1}) occurs at 4600–5000 m, which is >10 times the glacier terminus velocity. The average velocity of the 42 glaciers is highest in the 0°–5° slope range, and velocity decreases with increasing slope angle. East-facing glaciers have the highest velocity; for example, the east-facing Yengisogat glacier has an average velocity of 21.18 m · a^{-1}, while southwest-facing glaciers have the smallest velocity (17.02 m · a^{-1}).

(4) Different glacier types show different interannual streamline velocity variations. Stable glaciers have relatively stable interannual velocity variations, with consistent velocity values at the same locations across different years. Advancing and retreating glaciers show large interannual velocity fluctuations. Surging glaciers show location-dependent interannual velocity variations. Surging glaciers with advancing termini show little change in surface velocity, but terminus change velocity can exceed 100.00 m · a^{-1}, even reaching 500.00 m · a^{-1}.

(5) Longer and larger-area glaciers are prone to surging. Climate, avalanches, and topography are also major factors affecting glacier movement speed changes.

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