Postprint: Glacier Monitoring Research in Mount Everest National Nature Reserve Based on Multi-Source Remote Sensing Data

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Abstract

Glacier mass balance is an important indicator reflecting climate change and holds significant importance for regional ecological environment assessment and disaster prevention and control. Using Landsat series remote sensing imagery, this study employs the ratio threshold method and visual interpretation method to obtain glacier boundaries within the Mount Everest Nature Reserve from 1990 to 2020, investigating the distribution and variation characteristics of glacier area. Simultaneously, based on Differential Interferometric Short Baseline Time Series Analysis (SBAS-InSAR) technology, regional glacier deformation characteristics are monitored, and glacier mass balance processes are analyzed. The results indicate: (1) From 1990 to 2020, glaciers in the Mount Everest Nature Reserve experienced continuous retreat, with the retreat trend becoming more pronounced in the recent 10 years. The total glacier area within the reserve retreated by 247.16 km^2, with a change rate of -18.92%. (2) Glaciers in the reserve are mainly distributed within the elevation range of 5400–6200 m and slope gradient of 10°–15°, with the most significant retreat occurring in the 5400–5600 m elevation range and 10°–15° slope gradient range. (3) In 2020, the glacier deformation rate in the Mount Everest Nature Reserve ranged between -129.069–140.252 mm · a-1, with the most severe surface deformation subsidence occurring at elevations of 4200–4400 m and slope gradients of 40°–45°. (4) Rising temperatures and decreasing precipitation may be the primary factors causing glacier mass loss in the Mount Everest Nature Reserve. Meanwhile, spatial climate differences and terrain factors may also be important factors leading to variations in glacier mass balance.

Full Text

Glacier Monitoring in Qomolangma Nature Reserve Based on Multi-Source Remote Sensing Data

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Abstract

Glacier mass balance serves as a crucial indicator of climate change and holds significant importance for regional ecological environment assessment and disaster prevention. Based on Landsat series remote sensing imagery, this study employs the ratio threshold method and visual interpretation to extract glacier boundaries within Qomolangma Nature Reserve from 1990 to 2020, investigating the distribution and change characteristics of glacier area. Concurrently, the differential interferometric short-baseline time series analysis (SBAS-InSAR) technique is utilized to monitor regional glacier deformation characteristics and analyze glacier mass balance processes. The results indicate: (1) From 1990 to 2020, glaciers in Qomolangma Nature Reserve exhibited continuous retreat, with this trend becoming particularly pronounced in the last decade. The total glacier area within the reserve shrank by 247.16 km^2, representing a retreat rate of -18.92%. (2) Glaciers were predominantly distributed at altitudes of 5400–6200 m and slopes of 10°–15°, with the most significant retreat occurring within the altitude range of 5400–5600 m and slope range of 10°–15°. (3) In 2020, the average glacier deformation rate in Qomolangma Nature Reserve ranged between -129.069 and 140.252 $mm \cdot a^{-1}$, with the most severe surface deformation subsidence occurring at altitudes of 4200–4400 m and slopes of 40°–45°. (4) Rising temperatures and decreasing precipitation may be the primary factors driving glacier mass loss in Qomolangma Nature Reserve, while spatial climate differences and topographic factors may also constitute important causes of variations in glacier mass balance.

Keywords: multi-source remote sensing; SBAS-InSAR; glacier area; mass balance; Qomolangma Nature Reserve

Introduction

Glacier change is intimately connected to climate change and exerts significant influence on the climate system. Research demonstrates that glaciers respond sensitively to temperature variations, and their changing characteristics can reflect global climate change patterns. Therefore, investigating glacier area while monitoring glacier mass balance enhances scientific understanding of glacier response to climate change, increases comprehension of cryospheric ecosystem evolution, and provides scientific references for environmental adaptation strategies under global warming. With global climate warming, particularly since the 20th century, glacier retreat trends have become increasingly pronounced. While glacier melting within a certain period benefits water resource utilization, long-term glacier retreat not only triggers natural disasters such as glacial lake outburst floods and glacial debris flows but also contributes to sea-level rise, threatening coastal residents' lives and socio-economic development. Consequently, studying glacier changes against the backdrop of global change is of vital scientific and social significance for understanding regional glacier variations and their impacts, evaluating regional ecological environments, and exploring glacier-climate interactions. Glacier area distribution and change characteristics have consistently been a focal point of scientific research.

Although glacier area distribution and change studies are important for disaster prediction and prevention as well as water resource utilization in glaciated regions, mass balance serves as a crucial indicator of glacier change that directly reflects regional climate change characteristics and represents a vital link between glaciers and water resources. Traditional glacier monitoring relies primarily on field surveys, which offer high accuracy but are time-consuming and labor-intensive, making large-scale dynamic monitoring difficult. The development of remote sensing technology has ushered in a new era for glacier research. Optical remote sensing data are widely applied in glacier area studies due to their intuitive, clear, and easily interpretable advantages. Current monitoring of glacier surface mass balance changes predominantly employs mass balance models and geodetic methods based on multi-source digital elevation model (DEM) spatial matching. Although mass balance models have played important roles in glacier mass balance research, they suffer from parameter uncertainty and regional applicability issues. Currently, mature geodetic methods based on multi-source spatial matching are widely applied but encounter multi-source data matching problems. Glacier surface deformation, as an important parameter of glacier mass balance, can directly participate in glacier mass balance inversion, and its changing trend can intuitively reflect glacier mass balance variations. Therefore, studying glacier surface deformation characteristics can reflect glacier mass balance changes to a certain extent.

In recent years, radar remote sensing, particularly differential interferometric short-baseline time series analysis (SBAS-InSAR), has achieved multiple landmark results in millimeter-level surface deformation applications. Its advantages of high-precision observation, strong applicability, and capability for long-term monitoring of slow surface deformation provide new approaches for glacier surface mass balance research. This study focuses on glaciers in the Qomolangma Nature Reserve of the Himalayas, employing Landsat series optical imagery and Sentinel-1 radar data. Using the ratio threshold method and SBAS-InSAR technology, we monitor glacier area distribution and change characteristics in the Everest region, analyze spatiotemporal differentiation features of glacier surface deformation, and explore the response relationship between glacier mass balance and climate change, aiming to provide scientific basis for glacier disaster prevention and management in the Qomolangma protected area.

1 Study Area Overview

Qomolangma Nature Reserve is located at the border between China and Nepal [Figure 1: see original paper], representing the world's highest-altitude nature reserve. According to China's Second Glacier Inventory, the reserve contains 1,203 glaciers covering a total area of approximately 1,450.40 km^2, with the Rongbuk Glacier being the largest. The study area features a continental plateau climate with abundant sunlight and cold winters and cool summers. Data from the Gaer meteorological station indicate that the regional mean annual temperature is 2.1°C, sunshine percentage is 75.3%, and mean annual precipitation is 270.5 mm, with rain and heat occurring in the same season. Due to its unique and complex geographic location and climate conditions, Qomolangma Nature Reserve has become a hotspot for scientific research.

2 Data and Methods

2.1 Data Sources

2.1.1 Remote Sensing Imagery The Landsat series remote sensing imagery used in this study was obtained from the United States Geological Survey (https://earthexplorer.usgs.gov/) and the Geospatial Data Cloud (https://www.gscloud.cn/). To improve the accuracy of glacier boundary extraction, images with minimal cloud cover and snow were selected, with the final images listed in .

The Sentinel-1 satellite is a dual-satellite observation system designed by the European Space Agency for monitoring global-scale land, ocean topography, and polar regions. It carries a C-band synthetic aperture radar capable of providing continuous imagery. Ascending orbit images are concentrated at night, while descending orbit images are acquired during daytime. Since glacier thermal melting may cause image decorrelation, more stable ascending orbit data were selected for this study. This research chose Sentinel-1A ascending orbit data , with orbit files using precise orbit data provided by the European Space Agency (https://e4ftl01.cr.usgs.gov/), achieving an orbital data accuracy of 10 cm.

2.1.2 DEM Data Two types of DEM data were employed: SRTM DEM and ASTER GDEM, both with 30 m resolution. Although SRTM DEM is used for glacier boundary extraction, data gaps and anomalies occur due to specular reflection, echo lag, and radar shadow effects. ASTER GDEM exhibits smaller data gaps and better reflects geomorphic features. Furthermore, Long Sichun et al. processed different reference DEMs using InSAR technology, demonstrating that ASTER GDEM produces differential interferograms with less noise. Therefore, this study adopted ASTER GDEM for glacier boundary identification and elevation and slope calculations.

2.2 Research Methods

2.2.1 Glacier Boundary Extraction This study selected the highly accurate and effective ratio threshold method (band3/band5) to extract glacier boundaries in Qomolangma Nature Reserve. After comparing multiple experimental results, the optimal threshold for TM/ETM+ ratio images was determined to be 2.0. Decision tree classification was applied to obtain binary images, followed by visual interpretation. Meanwhile, results were corrected based on the Second Glacier Inventory data to improve glacier boundary interpretation accuracy [Figure 2: see original paper].

2.2.2 Glacier Area Change Calculation The annual average change rate was used to evaluate changes in total glacier area in Qomolangma Nature Reserve, calculated as follows:

$$APAC_i = \frac{\Delta S_i \times 100\%}{S_i \times T_i}$$

where ΔS_i represents the glacier area change in period i; S_i is the initial glacier area in period i; $APAC_i$ is the annual average change rate; and T_i is the time interval of period i.

2.2.3 Glacier Deformation Rate Monitoring Berardino et al. proposed the Small Baseline Subset (SBAS-InSAR) technique, which does not require master image selection and is insensitive to factors such as spatiotemporal decorrelation and atmospheric effects, achieving millimeter-level monitoring accuracy. The principle is as follows:

Assuming N images are acquired during the time period t_0 to t_n, M interferograms are generated through baseline combination. For the i-th interferogram generated from images at times t_a and t_b ($t_b > t_a$), the interferometric phase at pixel (x, y) is expressed as:

$$\delta\phi_i = \phi(t_b) - \phi(t_a) \approx \frac{4\pi}{\lambda}[d(t_b) - d(t_a)]$$

where $d(t_a)$ and $d(t_b)$ are the surface deformation amounts relative to the reference time t_0 at times t_a and t_b, respectively; λ is the radar wavelength; and ϕ_a and ϕ_b are the unwrapped phases corresponding to times t_a and t_b.

The unwrapped phase of the interferograms is:

$$\delta\phi = A\phi + \epsilon$$

where $\delta\phi$ is the interferometric phase; A is the coefficient matrix; and ϵ is the residual phase.

This study processed Sentinel-1 ascending orbit data using SBAS-InSAR technology to obtain deformation results, with the data processing workflow shown in [Figure 3: see original paper].

2.3 Accuracy Assessment

To evaluate the accuracy of glacier boundary extraction, a buffer analysis was conducted on the 2020 glacier boundaries. The error rate was calculated by dividing the buffer area by the total glacier area. The final error rate was small and met precision requirements .

3 Results

3.1 Distribution and Change Characteristics of Total Glacier Area

From 1990 to 2020, the glacier area in Qomolangma Nature Reserve showed an overall retreat, decreasing from 1,306.31 km^2 to 1,059.15 km^2, with an area change rate of -18.92%. The degree of glacier retreat varied across different periods . Specifically, from 1990 to 2000, the glacier area retreated by 11.48 km^2 with an annual change rate of -0.09% $\cdot$ a^{-1}. From 2000 to 2010, the glacier area retreated by 63.51 km^2 with an annual change rate of -0.49% $\cdot$ a^{-1}. From 2010 to 2020, the glacier area retreated by 172.17 km^2, with the retreat rate significantly higher than in the previous two periods, reaching an annual change rate of -1.63% $\cdot$ a^{-1}. In summary, glaciers in Qomolangma Nature Reserve have shown an accelerating retreat trend over the past 30 years, with the retreat becoming increasingly significant in recent years, consistent with glacier retreat trends in the Himalayan region.

3.2 Glacier Distribution and Change Characteristics by Altitude

Taking 200 m intervals, the distribution of glacier area by altitude in Qomolangma Nature Reserve from 1990 to 2020 was statistically analyzed. Using 2020 as an example, glaciers were most extensively distributed at 5600–5800 m, reaching 196.21 km^2 and accounting for 14.94% of the total glacier area in that period. Glaciers below 4800 m were sparsely distributed, likely due to temperature effects and limited water vapor supply, resulting in a dry and cold climate at low altitudes that is unfavorable for glacier development and accumulation. The altitude range of 5200–6400 m possesses favorable spatial positions and abundant precipitation, with temperatures decreasing as altitude increases, providing suitable conditions for glacier development. Glaciological theory suggests that a mountain may have one or more precipitation belts. The precipitation in high-altitude mountain glaciers shows distinct patterns with height. As altitude increases, the temperature of moist air on slopes decreases and saturation increases. When reaching a certain height, precipitation falls, forming the first precipitation belt. Glaciers and snow at high altitudes, with their low temperatures and sufficient water vapor, can lower the temperature of passing cloud clusters, thereby forming precipitation—the second major precipitation belt. Xie Zichu et al. believe that the Mount Qomolangma region has a relatively obvious "second major precipitation belt" due to local circulation effects. Japanese scholar Yasunari found that the second major precipitation belt in the Himalayas is distributed above 5000 m. Therefore, glacier accumulation at 5200–6400 m may depend on replenishment from the second major precipitation belt.

The total glacier retreat amount by altitude showed an initial increase followed by a decrease [Figure 4: see original paper]. The most significant retreat occurred at 5400–5600 m, with a retreat amount of 50.06 km^2, while almost no retreat occurred above 8000 m. Compared to the retreat amount, the total retreat rate showed a fluctuating decline, with a small peak of 30.93% at 5000–5200 m. It can be observed that low-altitude areas experienced smaller glacier retreat amounts but higher retreat rates, while high-altitude areas showed lower retreat amounts and rates. This may be because higher temperatures at low altitudes are unfavorable for glacier accumulation, resulting in high retreat rates despite small retreat amounts due to the limited glacier distribution area. In high-altitude areas, relatively low temperatures slow glacier melting, but the limited accumulation space results in low retreat rates and amounts.

3.3 Glacier Distribution and Change Characteristics by Slope

At 5° intervals, glacier slopes were divided into 12 grades. The distribution characteristics of glacier area by slope in Qomolangma Nature Reserve from 1990 to 2020 were similar across periods, showing an initial increase followed by a decrease with increasing slope [Figure 5: see original paper]. Using 2020 as an example, glaciers were most extensively distributed at 10°–15°, reaching 445.51 km^2 and accounting for 34.10% of the total glacier area in that period. The least distribution occurred at 55°–60°, with only 21.11 km^2 (1.62%). This indicates that glaciers in Qomolangma Nature Reserve are mainly distributed in relatively gentle areas, with minimal distribution in extremely flat or steep regions.

Over the past 30 years, both total glacier retreat amount and retreat rate by slope showed unimodal patterns. The largest retreat area occurred within the 10°–15° slope range, reaching 37.95 km^2, while the smallest retreat occurred at 55°–60°, with only 2.53 km^2. The highest retreat rate appeared at 20°–25°, while the lowest occurred at 55°–60°.

3.4 Glacier Deformation Characteristics

Based on SBAS-InSAR technology, glacier surface deformation information in Qomolangma Nature Reserve was obtained for 2020. The results show that the regional deformation rate ranged from -37.397 to 36.357 $mm \cdot a^{-1}$, with most ice tongue areas showing thinning trends while high-altitude areas showed the opposite trend.

Due to the lack of field measurement data, this study indirectly validated glacier deformation results using deformation results from non-glacier areas. Three non-glacier areas were selected [Figure 7: see original paper], and deformation statistics were calculated . The root mean square errors were 0.16 mm, 0.16 mm, and 0.17 mm, respectively, proving that the deformation results have high reliability.

3.4.1 Glacier Surface Deformation Characteristics by Altitude Using ArcGIS software and the zonal statistics tool, glacier deformation amounts at different altitudes were obtained [Figure 8: see original paper]. The results indicate that glaciers in different elevation zones exhibit different deformation trends, with most glaciers in the study area showing thinning. Glaciers below 5800 m showed varying degrees of subsidence, with the most severe subsidence occurring at 4200–4400 m, reaching -17.246 mm. Glaciers at 5800–6400 m showed slight uplift, with deformation amounts of 0.347 mm at 6200–6400 m. As mentioned earlier, glaciers at 5800–6400 m showed uplift. Combined with the previous discussion on glacier area, this suggests that the "second major precipitation belt" in Qomolangma Nature Reserve is likely located at 5200–6400 m, consistent with Yasunari's observation of a "second major precipitation belt" in the Himalayas.

Above 6400 m, glacier subsidence amounts fluctuated and increased with altitude, reaching -12.448 mm at 8000–8200 m. Low-altitude areas are affected by higher temperatures and lower humidity, causing glacier melting and thinning. High-altitude areas typically have sufficient space and abundant precipitation, facilitating glacier accumulation and showing uplift trends. However, severe subsidence in high-altitude areas in this study may be attributed to avalanches that caused deformation anomalies. It was verified that the Shishapangma region included in the study area experienced a major avalanche in October 2020. Overall, low-altitude areas are more prone to glacier thinning due to material ablation, while high-altitude areas tend to show uplift.

3.4.2 Glacier Surface Deformation Characteristics by Slope At 5° intervals, glaciers were divided into 12 grades [Figure 9: see original paper]. Glaciers in Qomolangma Nature Reserve showed varying deformation degrees across slopes. Glaciers at 0–50° showed subsidence trends, with deformation amounts increasing with slope. The most severe subsidence occurred within the 40°–45° range, reaching -1.401 mm. When the slope exceeded 50°, the thinning trend decreased, and uplift began to appear around 55°, reaching a maximum deformation amount of 1.545 mm at 55°–60°. The possible reason for this pattern is that steep slopes are generally located in high-altitude areas with low temperatures and slow glacier melting rates. Meanwhile, snow accumulation leads to significant uplift trends.

4 Discussion

Glacier area change exhibits a certain lag in response to climate, but climate change patterns can be directly presented through glacier mass balance. In recent decades, the Tibetan Plateau has experienced continuous temperature increases, with warming rates greater than those in the mid-latitude regions of the Northern Hemisphere. The warming trend in the eastern plateau has begun to slow down, while surface warming in the central and western regions has been more intense. Ren Jiawen et al. demonstrated that temperatures in the central Himalayas have been continuously rising, with more pronounced warming in summer. Over the past few decades, the warming rate in the Everest region has also been significantly higher than the average levels in China and worldwide. Precipitation changes in the Tibetan Plateau are influenced by westerly winds, the South Asian monsoon, and the plateau monsoon. Precipitation in the central Himalayas mainly originates from the Indian monsoon, but most glaciers in the study area are located on the northern slope of the Himalayas. The massive mountain range blocks monsoon precipitation, resulting in reduced precipitation on the northern slope. Additionally, ice core accumulation can directly reflect precipitation changes. Hou Shugui et al. pointed out, based on ice core records from the Far East Rongbuk Glacier, that glacier accumulation in the Everest region has been continuously decreasing, consistent with glacier retreat trends. Duan Keqin et al. speculated, based on Dasuopu ice core accumulation studies, that monsoon precipitation in the central Himalayan region would decrease with rising temperatures. In this study, glacier area in Qomolangma Nature Reserve has continuously retreated over the past 30 years, with overall thinning and mass balance deficit in recent years. This mass balance deficit state is consistent with previous research, and from a temporal perspective, glacier melting in the Everest region has been further intensifying. The glacier change trends in the study area correlate with recent temperature increases and precipitation decreases, suggesting that rising temperatures and reduced precipitation may be the main factors causing glacier retreat.

In addition to temperature and precipitation effects, factors such as glacier geographic location and topographic differences can lead to variations in solar radiation received, water vapor sources, and monsoon intensity, thereby affecting glacier changes. Since precipitation in the study area is influenced by the Indian monsoon and the study area is extensive, spatial differences in monsoon precipitation may contribute to mass balance variations. Furthermore, there is a close relationship between glacier retreat and glacial lake expansion. Accelerated glacier retreat in Qomolangma Nature Reserve has led to rapid glacial lake expansion. Temperature increases cause glacier melting, particularly at glacier termini, which increases meltwater and promotes terminal lake expansion. Meanwhile, rising temperatures increase lake evaporation. When evaporation is far less than meltwater supply, lakes continue to expand. Thus, glacier melting significantly impacts lake expansion, while glacial meltwater constitutes an important supply for lakes. Conversely, expanding lakes positively affect terminus melting, accelerating glacier terminal retreat.

Numerous debris-covered glaciers are distributed in Qomolangma Nature Reserve. Compared to bare ice areas, debris-covered glaciers have lower surface reflectivity and faster heat absorption, transferring more heat to sub-debris glaciers and surrounding ice, thereby promoting glacier melting. Thin debris cover accelerates glacier melting to some extent, while thickness beyond a certain threshold provides insulation. Black carbon, dust, and aerosols can enrich on glacier surfaces through dry and wet deposition. When glacier surfaces become polluted, debris-covered areas further expand, glacier albedo continues to decrease, heat absorption capacity increases, and glacier melting accelerates. In summary, rising temperatures and decreasing precipitation may be the main factors causing mass loss in most glaciers of Qomolangma Nature Reserve, while spatial climate differences and topographic factors may also be important causes of mass balance variations.

5 Conclusions

This study investigates glacier distribution and change characteristics in Qomolangma Nature Reserve using multi-source remote sensing data and analyzes glacier response relationships to climate change. The conclusions are as follows:

1. From 1990 to 2020, glacier area in Qomolangma Nature Reserve continuously retreated, with this trend becoming increasingly significant in recent years. Over the past 30 years, the total glacier area in the study area retreated by 247.16 km^2, with an annual change rate of -0.63% $\cdot a^{-1}$.

2. Glaciers in Qomolangma Nature Reserve were mainly distributed at altitudes of 5400–6200 m and slopes of 10°–15°, accounting for 34.10% and 14.94% of the total glacier area in the corresponding periods, respectively. The most significant retreat occurred at altitudes of 5400–5600 m and slopes of 10°–15°, with retreat amounts of 50.06 km^2 and 37.95 km^2, respectively.

3. In 2020, the average glacier deformation rate in Qomolangma Nature Reserve ranged between -129.069 and 140.252 $mm \cdot a^{-1}$. The most severe subsidence occurred at altitudes of 4200–4400 m and slopes of 40°–45°, with deformation amounts of -17.246 mm and -1.401 mm, respectively.

4. Rising temperatures and decreasing precipitation may be the primary factors causing mass loss in most glaciers of Qomolangma Nature Reserve. Meanwhile, spatial climate differences and topographic factors may also be important causes of mass balance variations.

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