Characteristics of Albedo Variation during the Melt Season of the Qiyi Glacier Based on Sentinel-2 and MODIS

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Abstract

With global warming, mountain glaciers are melting rapidly. As one of the key drivers of glacier ablation, glacier albedo plays an important role in assessing climate responses, predicting glacier evolution, and managing regional water resources. Taking the Qiyi Glacier as the study object, this study first used in situ albedo measurements to validate glacier albedo retrieved from Sentinel-2 and the Moderate Resolution Imaging Spectroradiometer (MODIS) daily albedo product, then analyzed the spatiotemporal variation characteristics of surface albedo on the Qiyi Glacier during the ablation seasons (May–September) from 2016 to 2024, and finally explored the relationships between albedo and climatic factors, surface impurities, and mass balance. The results show that: (1) the Sentinel-2 Multispectral Instrument albedo data have high accuracy, with spatial validation yielding a coefficient of determination (R2) of 0.845 and a root mean square error (RMSE) of 0.035, and temporal validation yielding R2=0.959 and RMSE=0.045; the MODIS daily albedo data have slightly lower accuracy but still exhibit good temporal consistency (R2=0.859, RMSE=0.123). (2) Albedo during the ablation season shows significant spatiotemporal differences: spatially, albedo reaches its maximum in the high-elevation central area and decreases toward both sides and the terminus, with the debris-covered terminus forming a low-value area; temporally, ablation-season albedo decreases from 0.66 in the early stage to 0.52 in the intense stage and then rises to 0.58 in the late stage, showing a decreasing trend on the interannual scale, while daily variations exhibit a "V"-shaped fluctuation under the combined influence of air temperature and precipitation. (3) Daily mean air temperature and positive accumulated temperature are negatively correlated with albedo, whereas precipitation amount and the number of precipitation days are positively correlated with albedo; impurities show high concentrations at low elevations and are mainly distributed at 4450~4600 m; the mean ablation-season albedo of the Qiyi Glacier has a strong positive linear correlation with annual mass balance. These findings help deepen the understanding of glacier ablation processes and mechanisms and provide a basis for the accurate simulation of glacier energy-mass balance.

Full Text

Characteristics of Albedo Variation during the Melt Season of the Qiyi Glacier Based on Sentinel-2 and MODIS

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Abstract: With global warming, mountain glaciers are melting rapidly. As one of the key driving factors of glacier melting, glacier albedo plays an important role in assessing climate response, predicting glacier evolution, and managing regional water resources. Taking the Qiyi Glacier as the study object, this study first used station-observed albedo data to validate Sentinel-2-derived glacier albedo and the daily albedo products of the Moderate Resolution Imaging Spectroradiometer (MODIS), and then analyzed the spatiotemporal variation characteristics of the surface albedo of the Qiyi Glacier during the melt seasons (May–September) from 2016 to 2024. Finally, the relationships between albedo and climatic factors, surface impurities, and mass balance were explored. The results show that: (1) Sentinel-2 multispectral imager albedo data have relatively high accuracy; spatial validation: the coefficient of determination (R^2) was 0.845 and the root mean square error (RMSE) was 0.035; temporal validation: $R^2 = 0.959$, RMSE=0.045. The accuracy of MODIS daily albedo data was slightly lower, but it still showed good temporal consistency ($R^2 = 0.859$, RMSE=0.123). (2) Albedo during the melt season exhibited significant spatiotemporal differences: spatially, albedo reached a peak in the central high-elevation area and decreased toward both sides and the terminus, with the terminus surface characterized by a low-value zone; temporally, melt-season albedo decreased from 0.66 in the early stage to 0.52 in the intense stage, then rose to 0.58 in the late stage. On an interannual scale it showed a declining trend, while daily changes presented a "V" -shaped fluctuation under the combined influence of air temperature and precipitation. (3) Daily mean air temperature and positive accumulated temperature were negatively correlated with albedo, whereas precipitation and precipitation days were positively correlated with albedo; impurities showed low-concentration enrichment at high elevations and were concentrated at 4450–4600 m; the mean albedo during the melt season of the Qiyi Glacier had a strong positive linear correlation with annual mass balance. The results of this study help deepen understanding of the glacier melting process and its mechanisms, and provide a basis for accurate simulation of glacier energy–mass balance.

Key words: Qiyi Glacier; Sentinel-2; MODIS; albedo; spatiotemporal variation

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Glaciers are an integral component of the Earth' s climate system and play important roles in indicating climate change, supplying freshwater resources, and regulating ecosystems[1]. In recent years, intensified global warming has caused accelerated melting and rapid area shrinkage of most glaciers, which has had major impacts on regional water-resource management and human society[2]. Glacier albedo, as a key parameter measuring the ability of a glacier surface to reflect solar radiation, is usually expressed as the ratio of upward solar radiation to incoming solar radiation. Under global warming, intensified glacier surface melting leads to reduced glacier albedo, and the "darkening effect" caused by reduced glacier albedo further intensifies glacier surface melting. This positive feedback mechanism is an important factor leading to glacier melt[3]. Influenced by the physical properties of ice and snow and by external environmental conditions, albedo varies significantly among different regions of the same glacier[4–5].

Observational data of glacier albedo include station data, reanalysis data, and remote-sensing data. Station data are obtained through in situ observations, such as by setting up meteorological stations on the glacier surface or using specialized albedometers for measurements. However, because of limitations in point-scale information, temporal continuity, and accessibility, they are difficult to use to reflect the overall albedo distribution of a glacier[6–7]. Reanalysis data are integrated data products generated by assimilating multiple types of observational information and atmospheric products, and are mainly used to drive model simulations and provide meteorological background fields. For example, Duanqin et al.[8] used ERA5-Land data to reconstruct the distribution of glacier surface albedo and simulate long-term glacier energy balance, pointing out that reliable and effective reanalysis data are a key factor affecting simulation accuracy. However, such data are usually less accurate than ground observations in mountainous regions.

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The original region, with a spatial resolution only at the 10^3 m level, has limitations when research is carried out on small mountain glaciers.

Remote-sensing observation technology, by virtue of its advantages such as broad spatial coverage, strong temporal continuity, and convenient data acquisition, has become a core means for studying the spatiotemporal variation of glacier albedo. Early low-resolution remote-sensing products (such as AVHRR and GLASS) are suitable for analysis over large snow- and ice-covered areas, but have limited ability to depict the fine spatial structures of mountain glaciers [9–10]. With the application of high-spatiotemporal-resolution satellites (such as the Landsat and Sentinel series), numerous studies have shown that such data have relatively high accuracy in retrieving mountain-glacier albedo and have been widely used in analyses of albedo changes for many glaciers, effectively revealing the response mechanism of albedo to melting [11–12].

At present, studies of small and medium-sized mountain glaciers mostly rely on remote-sensing data with relatively low spatial resolution, making it difficult to characterize albedo changes at fine spatiotemporal scales. Therefore, this paper introduces remote-sensing imagery with higher spatiotemporal resolution. In addition, because research on the driving factors of albedo changes on the

Qiyi Glacier remains relatively lacking, this paper combines Sentinel-2 multispectral instrument (MSI) albedo retrievals with Moderate Resolution Imaging Spectroradiometer (MODIS) daily albedo products to analyze the spatiotemporal variation characteristics of albedo during the ablation season of the Qiyi Glacier, and explores the relationships between climatic factors, surface impurities, mass balance, and spatiotemporal changes in albedo, providing a basis for glacier ablation in mountainous areas as well as mechanisms of water resources and climate-change response in alpine mountain regions.

1 Data and Methods

1.1 Overview of the Study Area

Qiyi Glacier ($39°14'13''N, 97°45'20''E$, glacier inventory number: 5Y437C18) is located on the northern slope of the Tuolai Mountains in the middle section of the Qilian Mountains. It is a valley glacier belonging to the Shule River-mountain valley glacier system. The glacier surface is partly covered by debris. The glacier area is approximately 2.6 km^2, its length is approximately 3.6 km, the terminus elevation is 4223.7 m, the highest point is 5114.7 m, and its overall aspect is northward (Fig. 1a–b) [13–14]. The region is mainly controlled by the westerly circulation. The mean air temperature ranges from -2 to $0\,°C$, and annual precipitation is approximately 270–450 mm, of which summer precipitation accounts for 80%-

(a) Regional map

(b) Qiyi Glacier

Legend
Automatic weather station
Spectrometer measurement_20230821
Spectrometer measurement_20240810
Elevation/m
5050
4248

Legend
Weather station
Qiyi Glacier
River
Glacier
Lake
Elevation/m
5792
1920

(c) Field spectrometer measurement

Fig. 2 Workflow of glacier surface albedo retrieval from Sentinel-2 MSI images

Figure 1: Fig. 2 Workflow of glacier surface albedo retrieval from Sentinel-2 MSI images

(d) Automatic weather station

图 1 研究区示意图及实测所需仪器

Fig. 1 Schematic diagram of the study area and instruments used for field measurements

95%[^15]. UAV measurements in 2023 showed that the glacier area had shrunk to 2.434 km^2; compared with the period of the second glacier inventory, the area had decreased by about 6.3% over nearly 10 years.

1.2 Data Sources

1.2.1 Sentinel-2A/B Satellite Multispectral Instrument (MSI) Imagery

Sentinel-2 consists of two satellites in the same orbit launched by the European Space Agency. Among them, the Sentinel-2A satellite was launched in June 2015, and the Sentinel-2B satellite was launched in March 2017; the overpass time is 10:30 a.m. local time, and the revisit period of the two satellites is 5 d[^16]. In this study, 65 Sentinel-2A/B remote-sensing images covering the Qiyi Glacier region during the ablation seasons from 2016 to 2024 were obtained from the official website of the European Space Agency. All selected images were acquired under clear-sky conditions without rain or fog cover. They were used as the original data for remote-sensing retrieval of glacier surface albedo, and all bands were resampled to 10 m. To address the problem of conversion among different temporal scales, this study used the mean value of all images within the study time interval as the glacier surface albedo for that period.

Because Sentinel-2 data are raw digital quantized values, a series of processing steps is required to obtain physically meaningful albedo data. The main steps in the retrieval workflow include radiometric calibration, atmospheric correction, topographic correction, and narrow-to-broadband conversion (Fig. 2).

Figure text: Original image; radiometric calibration; top-of-atmosphere radiance; atmospheric correction and topographic correction; surface spectral reflectance; narrow-to-broadband conversion; surface broadband reflectance.

Fig. 2 Workflow of glacier surface albedo retrieval from Sentinel-2 MSI images

(1) Radiometric calibration: Radiometric calibration is a basic step in remote-sensing data processing, intended to convert the original digital quantized values recorded by the sensor into radiance or reflectance values with physical meaning.

(2) Atmospheric correction: In this study, the FLAASH model was used for atmospheric correction to reduce or eliminate the influence of the atmosphere on electromagnetic waves reflected or emitted by ground objects.

(3) Topographic correction: Qiyi Glacier is located in the Qilian Mountains, where the terrain is complex. Topographic effects can distort the spectral characteristics of ground objects. To more realistically reflect the spectral characteristics of the objects themselves, this study adopted the improved CIVICO topographic correction model proposed by Qin Chun et al.[^17]. The core of this improved model is to classify slopes and combine solar position with a digital elevation model to extract shaded and sunlit slopes, and then calculate the correction coefficient C_λ. Specifically, using the solar azimuth angle φ recorded in the Sentinel-2 image metadata, slopes within an angular range of 60° in the direction of the solar rays ($\varphi \pm 30°$) are defined as sunlit slopes, and slopes within an angular range of 60° opposite to the solar rays ($180 + \varphi \pm 30°$) are defined as shaded slopes. The following formulas are used to perform topographic correction on the atmospherically corrected image:

$$L_{\mathrm{H}} = L_{\mathrm{S}} + L_{\mathrm{S}} \times \frac{\mu_{\mathrm{K}} - x}{\mu_{\mathrm{K}}} \qquad (1)$$

$$L_{\mathrm{H}} = L_{\mathrm{S}} + L_{\mathrm{S}} \times \frac{\mu_{\mathrm{K}} - x}{\mu_{\mathrm{K}}} \times C_\lambda \qquad (2)$$

$$C_\lambda = \frac{S_\lambda - N_\lambda}{S_\lambda \times \frac{\mu_{\mathrm{S}} - \mu_{\mathrm{K}}}{\mu_{\mathrm{K}}} - N_\lambda \times \frac{\mu_{\mathrm{N}} - \mu_{\mathrm{K}}}{\mu_{\mathrm{K}}}} \qquad (3)$$

where L_{H} is the corrected radiance value of the ground object; L_{S} is the original radiance value of the image; μ_{K} is the mean value after stretching the terrain-shadow map from 0–1 to 0–255; x is the pixel value corresponding to the terrain-shadow map after stretching from 0–1 to 0–255; C_λ is the correction coefficient; S_λ and N_λ are the mean values of sunlit slopes and shaded slopes in the image, respectively; and μ_{S} and μ_{N} are the mean values of sunlit slopes and shaded slopes, respectively, on the stretched terrain-shadow map.

(4) Narrow-to-broadband conversion: Remote-sensing sensors acquire discontinuous reflectance data within specific narrow spectral ranges. Therefore, the reflectance of multiple narrow bands recorded by the sensor must be converted into a single broadband albedo. This paper adopts the conversion relationship between reflectance and broadband albedo proposed by Li et al.[^18] for Sentinel-2 MSI imagery:

$$\alpha_{\text{Snow SW}} = -0.1992 b_2 + 2.3002 b_3 - 1.9121 b_4 + 0.6715 b_{8\mathrm{A}} - 2.2728 b_{11} + 1.9341 b_{12} - 0.0001 \qquad (4)$$

where $\alpha_{\text{Snow SW}}$ is the albedo retrieved for the snow/ice surface; b_2, b_3, b_4, b_{8A}, b_{11}, and b_{12} are the corrected reflectance values of bands 2, 3, 4, 8A, 11, and 12, respectively.

1.2.2 MOD10A1/MYD10A1 Albedo Products

MOD10A1 carried on the Terra satellite and MYD10A1 carried on the Aqua satellite are derived from the U.S. National Snow and Ice Data Center, with a spatial resolution of 500 m and a temporal resolution of 1 d. The products are stored in EOS-HDF format and provide a snow albedo data layer[^19]. This study selected the ···

The orbit number was h25v05, and the data were images from the ablation seasons of 2016–2024. The processing workflow followed these steps: the command-line function of MODIS Reprojection Tool was used to perform batch projection conversion and format processing of the original data; subsequently, scripts were written in ENVI to implement batch clipping, band operations, and data fusion of the images. The fusion process adopted the optimization strategy proposed by Hu Anjian et al.

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, integrating dual-satellite data and using linear interpolation to fill missing dates in the MODIS products. Finally, the QY_MOD daily albedo product for the Qiyi Glacier region during the 2016–2024 ablation seasons was generated.

1.2.3 ASD FieldSpec 3 spectroradiometer

In this study, an ASD FieldSpec 3 high-performance portable ground spectroradiometer (spectral range 350–2500 nm) was used for field measurements on August 21, 2023 and August 10, 2024, respectively (Fig. 1b–c). Observations were conducted under clear-sky, cloudless atmospheric conditions and followed the principle of representative sampling. Referring to the standard procedure described by Chen et al.

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, sample points were arranged along the elevation gradient of the glacier. Sampling fully considered the spectral characteristics of different glacier surface states: the 2023 measurements corresponded to the bare-ice surface state after continuous glacier ablation, whereas the 2024 measurements were conducted after a preceding snowfall event, with supplementary sampling of surfaces covered by fresh snow. The sample types covered fresh snow, coarse-grained snow, dirty ice, and surface debris. The raw spectral data obtained were processed in ViewSpecPro 5.6 software by removing anomalous values and averaging, yielding broadband albedo for each sample point.

1.2.4 Digital orthophoto imagery

To obtain the fine geomorphological characteristics of Qiyi Glacier, in August 2023 this study deployed a glacier-surface data acquisition system consisting of a DJI Matrice M300 RTK UAV platform and a Zenmuse L1 sensor. Through the standard processing workflow of DJI Terra and LiDAR360 software (including raw data decoding, point-cloud denoising and smoothing, registration and merging, etc.), digital orthophoto imagery with a resolution of 0.05 m was generated.

1.2.5 Meteorological data

In this study, a ClimaVue™50 automatic weather station (AWS) was installed on a pure ice surface at an elevation of 4500 m on the lower underlying surface in the middle section of Qiyi Glacier (Fig. 1d), and continuous observations of the underlying-surface albedo, air temperature, and cumulative precipitation were conducted during 2023–2024. To construct a continuous observational meteorological dataset covering the entire study period, this study introduced daily mean air temperature and precipitation data from the nearest national basic meteorological station with a similar climatic background, the Qinghai Tuole station (station number 52633, elevation 3367 m). The data were obtained from the China Meteorological Data Network. Considering the significant elevation difference between the meteorological station and the main glacier area, the meteorological data were altitude-gradient corrected according to the recognized vertical temperature lapse rate of 0.61 ℃ · $(100\ \text{m})^{-1}$ and vertical precipitation increase rate of 9% · $(100\ \text{m})^{-1}$ for the Qilian Mountains

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2 Results and analysis

2.1 Validation results of field-site albedo data against remotely sensed retrieved albedo products

In this study, field-measured ASD spectral data and AWS observational data were used to validate the accuracy of albedo products retrieved from Sentinel-2 MSI and MODIS. At the spatial scale, Sentinel-2 MSI albedo was compared with the retrieval results from the ASD spectroradiometer (Fig. 3a); the root mean square error (RMSE) between them was 0.035, and the coefficient of determination (R^2) was 0.845. At the temporal scale, it was compared with the albedo observed by the AWS (Fig. 3b), with an RMSE of 0.045 and R^2 of 0.959. The results indicate that the Sentinel-2 MSI retrieval method adopted in this study is suitable for high-spatial-resolution albedo research on Qiyi Glacier. Possible sources of this error include incomplete terrain correction caused by complex topography, the limited number of available validation data samples, and pixel saturation over ice-and-snow surfaces. The QY_MOD product was compared with AWS-measured albedo at the temporal scale (Fig. 3c), with an RMSE of 0.123 and R^2 of 0.859; the relatively high R^2 indicates that the two

Fig. 3 Validation between the remotely retrieved albedo and the in-situ measured albedo

Figure 2: Fig. 3 Validation between the remotely retrieved albedo and the in-situ measured albedo

Note: ASD denotes the data measured by the ASD FieldSpec 3 spectroradiometer; AWS denotes the data measured by the automatic weather station; R^2 denotes the coefficient of determination. The same below.

Fig. 3 Validation between the remotely retrieved albedo and the in-situ measured albedo

shows strong synchrony in its temporal variation trend. Therefore, it can serve as supplementary data for the long-term spatiotemporal evolution of albedo during the ablation season of the Qiyi Glacier. In combination with the study by Liang[1], the errors in the QY_MOD albedo product mainly arise from the inherent bias of the bidirectional reflectance distribution function model on which MODIS relies, mixed-pixel effects, and cloud cover.

2.2 Spatial variation of glacier albedo during the ablation season

In this study, Sentinel-2 MSI imagery was used to retrieve the mean albedo spatial distributions of the Qiyi Glacier for three stages of the ablation season from 2016 to 2024—the early ablation period (May–June), the intense ablation period (July–August), and the late ablation period (September) (Figs. 4–5). Throughout the ablation season, the surface albedo of the Qiyi Glacier shows a clear increasing trend with elevation. In areas below 4350 m a.s.l., because the terminus of the glacier is covered by debris, zones with albedo lower than 0.2 occur. In the elevation ranges of 4350–4450 m and 4550–4650 m, the spatial distribution of albedo is uneven and shows transitional characteristics; in the high-elevation zone of 4750–5050 m, albedo increases markedly to above 0.6 and reaches a peak at about 4850 m. As elevation rises to the glacier margin, albedo decreases. This is because regions near the glacier margin at the glacier head are affected by heat conduction from surrounding bare rock; enhanced heat absorption intensifies ablation, thereby causing a reduction in albedo.

Glacier albedo exhibits spatially differentiated characteristics in different ablation periods. In the early, intense, and late ablation periods, the mean rates of increase in albedo with elevation are $0.037 \cdot (100\text{ m})\hat{}-1$, $0.109 \cdot (100\text{ m})\hat{}-1$, and $0.044 \cdot (100\text{ m})\hat{}-1$, respectively. In the early ablation period, the overall glacier surface albedo is relatively high (about 60% of the area is 0.6–0.7, and 36% is 0.7–0.8), and the spatial distribution shows significant vertical differentiation: in the debris-covered area at the terminus below 4350 m a.s.l., albedo is

[1]Reference number as shown on the page.

Fig. 5 Relationship between albedo and altitude zones across the Qiyi Glacier in the ablation periods from 2016 to 2024

Figure 3: Fig. 5 Relationship between albedo and altitude zones across the Qiyi Glacier in the ablation periods from 2016 to 2024

lower than 0.5; at 4350–4550 m it remains at 0.6–0.7; and in the high-elevation zone of 4650–5050 m it further increases to 0.7–0.8, generally increasing with elevation. During the intense ablation period, the banded structure of the spatial distribution of albedo is clear, specifically manifested as follows: in areas below 4350 m, albedo drops below 0.4 and ablation is intense; 4350–4550 m is

(a) Early ablation period (b) Intense ablation period

(b) Late ablation period (d) Entire ablation season

Legend

—Contour lines

Albedo

Class
<0.2
0.2–0.4
0.4–0.5
0.5–0.6
0.6–0.7
0.7–0.8
>0.8

0 0.4 km

Fig. 4 Spatial distributions of the mean albedo of the Qiyi Glacier from 2016 to 2024

Fig. 5 Relationship between albedo and altitude zones across the Qiyi Glacier in the ablation periods from 2016 to 2024

0.4–0.5, and the ablation intensity is high and widely distributed; at 4550–4750 m it rises to 0.5–0.6; in areas above 4750 m, the albedo increases from the glacier margins toward the central ridge. In the late ablation period, about 30% of the area has an albedo of 0.5–0.6, about 60% of the area is 0.6–0.7, and about 7% of the area is 0.7–0.8. The spatial variation amplitude of glacier albedo decreases, showing an overall increasing trend, and glacier ablation weakens.

Fig. 6 Heatmap of the mean albedo distribution for the Qiyi Glacier in different periods from 2016 to 2024

Figure 4: Fig. 6 Heatmap of the mean albedo distribution for the Qiyi Glacier in different periods from 2016 to 2024

2.3 Interannual variation in glacier albedo during the ablation season

From 2016 to 2024, the overall albedo during the ablation season of the Qiyi Glacier showed a decreasing trend (Fig. 6), which is consistent with the observed facts of continuous glacier ablation and area shrinkage. Based on precipitation data, the cumulative precipitation during the ablation seasons of 2017, 2018, 2019, and 2022 all exceeded 300 mm, with 2017 being the highest, reaching 401.2 mm. Correspondingly, the mean albedo during the ablation season in 2017 was a relatively high value for the study period. The albedo in rainy years was slightly higher than that in other years, reflecting the significant influence of ablation-season precipitation on annual albedo changes. The ablation-season albedo in 2024 was relatively low, mainly because the mean temperature from May to September in that year was the highest during the study period. In the early ablation period, the multi-year superposed mean value was 0.66, indicating that glacier ablation during this period was not pronounced. During the intense ablation period, the multi-year mean value was 0.52, and the annual—

(a) Early ablation period

(b) Intense ablation period

(c) Late ablation period

(d) Entire ablation season

Fig. 6 Heatmap of the mean albedo distribution for the Qiyi Glacier in different periods from 2016 to 2024

The interannual variation differences are obvious. Glacier ablation is affected by the temperature and precipitation of the current year. In July–August each year, the snowfall frequency in the Qiyi Glacier region is the highest; daytime noon temperatures mostly remain in the high-value range of 7 °C, and the albedo at the glacier terminus is the lowest. At the same time, the glacier top receives more snowfall, and because of the lower temperature, the glacier albedo remains at 0.6–0.7. In the late ablation period, glacier ablation weakens and the albedo rises again, with a multi-year mean value of 0.58.

2.4 Daily variation of glacier albedo during the ablation season

Based on the QY_MOD albedo product, this study plotted the daily variation curves of surface albedo for Qiyi Glacier during the ablation seasons from 2016 to 2024 (Fig. 7). From May to September each year, glacier albedo generally shows

Fig. 7 Relationship between daily albedo variations and temperature/precipitation from 2016 to 2024

Figure 5: Fig. 7 Relationship between daily albedo variations and temperature/precipitation from 2016 to 2024

a "V" -shaped variation. In May, albedo is usually in a high-value range (0.7–0.8); from late June onward, albedo gradually decreases; in July–August, albedo drops to the lowest level of the ablation season, with the July mean ranging from 0.31 to 0.38 and the August mean ranging from 0.26 to 0.37. During this period, glacier mass loss is the most severe, and bare ice is widely exposed, causing albedo to decline sharply and further intensifying glacier ablation. Entering September, albedo rises slightly; however, because precipitation decreases and local air temperature is higher than the snow–ice melting threshold, albedo still remains low during certain periods.

The daily variation of surface albedo on Qiyi Glacier is extremely pronounced. Taking 2024 as an example, after albedo reached its maximum value of 0.62 on August 1, it dropped within only one week to the minimum value of 0.13 on August 7. Similarly, continuous decreases also occurred during periods such as July 22–29 and August 15–23, reflecting the short-term transition of glacier surface cover type from fresh snow to old snow and then to bare ice. In addition, the diurnal variation of albedo also shows clear differences, which can be divided specifically into: (1) logarithmic type: albedo is highest when the sun first rises in the morning, then drops sharply around noon and tends to stabilize in the afternoon. (2) asymmetric U type: albedo is relatively high in the morning and afternoon, with the morning slightly higher than the afternoon, and reaches the daily minimum around noon. (3) stable type: albedo fluctuates little throughout the day, mostly occurring on cloudy or overcast days.

3 Discussion

3.1 Response of Qiyi Glacier albedo to temperature and precipitation

Qiyi Glacier is a continental glacier. Its development is more susceptible to changes in temperature and precipitation: temperature determines glacier ablation, precipitation determines glacier accumulation, and together they determine the properties, development, and evolution of the glacier[^25]. Based on daily observational data from the Tuole meteorological station from 2016 to 2024, this study selected daily mean temperature, daily maximum temperature, daily minimum

Note: The horizontal axis represents date, with May 1 as day 1; the time period is May 1–September 30, totaling 153 d.

Figure 7 Daily albedo variations from 2016 to 2024 and their relationship with temperature and precipitation

Fig. 7 Relationship between daily albedo variations and temperature/precipitation from 2016 to 2024

low temperature, positive accumulated temperature, precipitation, and number of precipitation days, to analyze the influence of meteorological factors on albedo changes (Table 1). The correlation analysis shows that daily mean temperature and positive accumulated temperature are negatively correlated with albedo in different periods, whereas precipitation and number of precipitation days are positively correlated. Monthly-scale analysis indicates that May is in the warming stage, but precipitation remains weak, and air temperature is the dominant factor maintaining high albedo changes during this period. In June, albedo changes are mainly affected by precipitation and consecutive precipitation days. Entering July–August, the daytime mean air temperature of Qiyi Glacier is generally maintained at 3–7 ℃, and the positive accumulated temperature continuously increases, promoting the transformation of the glacier surface from snow cover to bare ice, causing albedo to drop sharply and accelerating ablation. In September, air temperature decreases and precipitation decreases; albedo is mainly affected by changes in precipitation, while also showing a relatively strong correlation with daily maximum temperature.

Table 1 Statistics of correlation coefficients between albedo and meteorological data in different periods of Qiyi Glacier

Tab. 1 Correlation coefficients between albedo and meteorological variables for the Qiyi Glacier during different periods

Month	Daily mean temperature/℃	Daily maximum temperature/℃	Daily minimum temperature/℃	Positive accumulated temperature/℃ · d	Precipitation/mm	Precipitation days/d
5	−0.4470*	−0.1773*	0.0192	−0.3521*	0.1263	0.1402
6	−0.2783*	−0.1078	0.1504	−0.2596*	0.4261*	0.4786*
7	−0.3452*	−0.1154	−0.0203	−0.3452*	0.2485*	0.2424*
8	−0.2837*	−0.0816	0.1702*	−0.2844*	0.1709*	0.1693*
9	−0.1156	−0.3764*	0.0368	−0.0832*	0.2649*	0.0477

Note: * indicates significance at the $P<0.05$ level.

3.2 Influence of impurities on albedo

Impurities on the glacier surface strongly absorb solar shortwave radiation, reducing the reflected energy of the ice surface, leading to a decrease in albedo and enhanced heat absorption[26]. To investigate the physical properties of supraglacial impurities on Qiyi Glacier and their influence on albedo, this study

Fig. 8 Relationship between supraglacial impurity concentration and elevation during the ablation period in 2024

Figure 6: Fig. 8 Relationship between supraglacial impurity concentration and elevation during the ablation period in 2024

carried out ice-snow sample collection and laboratory analysis from July to September 2024. Sampling transects were arranged from top to bottom along the glacier’ s elevation gradient, and comparative samples were collected at different positions at the same elevation; GPS was used to record the locations and numbers of sampling points. The samples were then transported back to the laboratory, where their moisture was dried in an oven, particles were weighed, and impurity concentration was calculated. A laser particle-size analyzer was used to conduct particle-size grading experiments on the particulate samples, and according to sedimentological classification standards they were divided into grain-size intervals of 0-2 μm, 2-16 μm, 16-64 μm, and 64-3500 μm.

Spatial distribution analysis of supraglacial impurity concentration (Fig. 8) shows that, overall, it decreases with increasing elevation. From the perspective of temporal dynamics, during the intense ablation period (July 30, August 3, August 7, and August 10), concentrations were concentrated in the middle- and low-elevation zones of 4450-4600 m; whereas in the late ablation period (September 10 and September 13), concentrations decreased significantly. This is consistent with the covering effect of snowfall events occurring during the period on the glacier surface. Analysis based on spectrometer observations shows that supraglacial impurity concentration is a key factor affecting albedo. When the glacier surface is aged snow, the contribution rate of impurities to albedo reduction is about 38%; whereas on bare-ice surfaces where impurities are more enriched, the contribution rate is as high as 68%.

Fig. 8 Relationship between supraglacial impurity concentration and elevation during the ablation period in 2024

As shown in Fig. 9, the surface impurities of Qiyi Glacier are dominated by silt-sized particles (3-35 μm), with the main peak concentrated in fine silt (8-10 μm) and coarse silt (16-21 μm); the secondary peak appears in sand-sized particles (220-600 μm). In terms of the proportions of each particle size, fine particles smaller than 2 μm account for about 8.2%; fine silt of 2-16 μm has the highest proportion, reaching 53.4%; coarse silt of 16-64 μm accounts for 31.6%; and sandy particles larger than 64 μm account for about 6.8%. This complex particle-size composition reflects the multiple sources of supraglacial impurities during the ablation period, including atmospheric dry and wet deposition, rock debris transported by glacier erosion, and human

activities and industrial emissions, etc.

27–28

Fig. 9

Figure 7: Fig. 9

Fig. 10

Figure 8: Fig. 10

. The average particle size on the glacier surface is approximately 26.5 μm; these coarse-grained light-absorbing impurities, by virtue of their strong solar-radiation absorption capacity, significantly reduce the surface albedo and thus become a key driving factor accelerating glacier ablation. Field observations likewise show that these impurity particles often aggregate on the glacier surface in "patches" or "bands," forming areas with extremely low albedo. This spatially uneven enrichment effect further amplifies the negative impact of impurities on the glacier energy balance.

3.3 Relationship between surface albedo and the annual mass balance of the glacier

Variations in surface albedo dominate shortwave net radiation and are a core factor regulating the energy–mass balance of mountain glaciers; their contribution to mass loss can exceed 80%

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. To quantify the relationship between albedo and mass balance, this study established a correlation model between the mean albedo during the ablation season from 2016 to 2024 and the contemporaneously measured mass balance (Fig. 10).

Fig. 9 Natural frequency distribution curve of particle sizes in supraglacial impurity from the Qiyi Glacier

Fig. 10 Correlation between mass balance and mean albedo and their interannual variability of the Qiyi Glacier from 2016 to 2024

The results show that the two are significantly positively correlated, especially during the intense ablation period, when the correlation is strongest, with R^2 as high as 0.69 ($P < 0.005$). The correlation for the entire ablation season remains significant, with R^2 of 0.56 ($P < 0.05$), indicating that a decrease in summer albedo directly intensifies glacier mass loss. The equilibrium-line altitude (ELA) divides a glacier into an accumulation zone and an ablation zone, corresponding respectively to positive and negative energy balance. During the study period, the ELA of Qiyi Glacier was generally maintained at a high altitude above 5000 m. In particular, in 2016, 2018, 2022, and 2023, the ELA even exceeded the highest point of the glacier, and the glacier was in a state of net ablation, with no effective mass accumulation zone[^30]. Qiyi Glacier was in long-term shrinkage. During 2004–2015, the mean annual mass balance was −413 mm w.e., with a cumulative value of −4953 mm w.e. During 2016–2024, glacier mass loss showed an accelerating trend: the mean annual mass balance decreased to −709 mm w.e., and the cumulative value reached −6385 mm w.e. The annual mass balance and the mean albedo during the intense ablation period exhibited nearly synchronous fluctuations, with relatively large interannual variability. Quantitative analysis indicates that, with other conditions unchanged, for every 0.01 decrease in albedo during the intense ablation period, the annual mass balance decreases by about 100 mm w.e. Therefore, the reduction of albedo during the ablation season is one of the key factors intensifying the mass loss of Qiyi Glacier.

4 Conclusion

(1) The data validation results show that Sentinel-2 retrieved albedo is consistent with measured data at both spatial and temporal scales, with RMSE values of 0.035 and 0.045, and R^2 values as high as 0.845 and 0.959, respectively. Temporal validation of MODIS products against measured data gives an RMSE of 0.123 and an R^2 of 0.859. Therefore, the above products have good applicability for conducting research on the albedo of Qiyi Glacier.

(2) The ablation-season albedo of Qiyi Glacier shows significant spatiotemporal variation. Spatially, albedo increases with elevation and from the glacier margins toward the center; temporally, the annual mean albedo fluctuates downward, and within the ablation season it exhibits a "high-low-high" "V" -shaped pattern, with the lowest mean value (0.52) during the intense ablation period.

(3) Air temperature is the dominant factor in ablation-season albedo change and is strongly negatively correlated with albedo; precipitation is positively correlated with albedo by providing snow accumulation; surface impurities are dominated by sand and dust with a mean particle size of 26.5 μm, and the enrichment of coarse particles is an important surface factor leading to reduced albedo.

(4) The mass balance of Qiyi Glacier shows high sensitivity to ablation-season albedo. For every 0.01 decrease in albedo during the intense ablation period, the annual mass balance deficit is about 100 mm w.e.

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Albedo variation characteristics of the Qiyi Glacier during the ablation season based on Sentinel-2 and MODIS data

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Abstract: Mountain glaciers are rapidly melting owing to global warming. Glacier albedo is a key driver of glacial ablation. Glacier albedo plays a critical role in regional water resource management and the assessment of climate interactions by enabling predictions of future glacial evolution. Herein, the Sentinel-2-derived glacier albedo and Moderate Resolution Imaging Spectroradiometer (MODIS) daily albedo products of the Qiyi Glacier were first validated using in situ-measured albedo data. Next, the spatiotemporal characteristics of surface albedo during the ablation seasons (May–September) of 2016–2024 were analyzed. Finally, the relationships between albedo and climatic factors, surface impurities, and mass balance were explored. The key findings were as follows: (1) Sentinel-2 MSI albedo data were highly accurate. In the spatial validation, the coefficient of determination (R^2) was 0.845 and the root mean square error (RMSE) was 0.035, whereas in the temporal validation, R^2 was 0.959 and the RMSE was 0.045. MODIS daily albedo data exhibited slightly lower accuracy but maintained good temporal consistency (R^2=0.859, RMSE=0.123). (2) Ablation-season albedo exhibited significant spatiotemporal heterogeneity. Spatially, albedo peaked in the high-altitude central zone, gradually decreasing toward the margins and terminus, where supraglacial debris formed low-albedo regions. Temporally, albedo decreased from 0.66 in the early ablation season to 0.52 during the intense melting phase and then increased to 0.58 by the late season. Interannual trends showed a gradual decrease, while daily trends exhibited V-shaped variations caused by temperature-precipitation interactions. (3) Correlation analysis revealed negative relationships between albedo and daily mean temperatures and positive temperature sums, as well as positive correlations between albedo and precipitation volume and rainy days. The results also showed that impurities were concentrated at lower elevations (4450–4600 m). Moreover, the ablation-season average albedo of the Qiyi Glacier exhibited a strong positive linear correlation with the annual mass balance. This study enhances the understanding of glacial ablation processes and mechanisms, providing a theoretical basis for precise modeling of energy and mass balance in glacial systems.

Keywords: Qiyi Glacier; Sentinel-2; MODIS; albedo; spatiotemporal variation

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