

Region-wide glacier area and mass budgets for the Shaksgam River Basin, Karakoram Mountains, during 2000–2016 postprint

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Date: 2021-02-10T00:00:00+00:00

Abstract

The Karakoram Mountains are well known for their widespread surge-type glaciers and slight glacier mass gains. On the one hand, glaciers are one of the sensitive indicators of climate change, their area and thickness will adjust with climate change. On the other hand, glaciers provide freshwater resources for agricultural irrigation and hydroelectric generation in the downstream areas of the Shaksgam River Basin (SRB) in western China. The shrinkage of glaciers caused by climate change can significantly affect the security and sustainable development of regional water resources. In this study, we analyzed the changes in glacier area from 2000 to 2016 in the SRB using Landsat TM (Thematic Mapper)/ETM+ (Enhanced Mapper Plus)/OLI (Operational Land Imager) images. It is shown that the SRB contained 472 glaciers, with an area of 1840.3 km², in 2016. The glacier area decreased by 0.14%/a since 2000, and the shrinkage of glacier in the southeast, east and south directions were the most, while the northeast, north directions were the least. Debris-covered area accounted for 8.0% of the total glacier area. We estimated elevation and mass changes using the 1 arc-second SRTM (Shuttle Radar Topography Mission) DEM (Digital Elevation Model) (2000) and the resolution of 8 m HMA (High Mountain Asia) DEM (2016). An average thickness of 0.08 (± 0.03) m/a, or a slight mass increase of 0.06 (± 0.02) m w.e./a has been obtained since 2000. We found thinning was significantly lesser on the clean ice than the debris-covered ice. In addition, the elevation of glacier surface is spatially heterogeneous, showing that the mass accumulation is dominant in high altitude regions, and the main mass loss is in low altitude regions, excluding the surge-type glacier. For surge-type glaciers, the mass may transfer from the reservoir to the receiving area rapidly when surges, then resulting in an advance of glacier terminus. The main surge mechanism is still unclear, it is worth noting that the surge did not increase the glacier mass in this study.

Full Text

Preamble

Region-wide Glacier Area and Mass Budgets for the Shaksgam River Basin, Karakoram Mountains, during 2000-2016

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Abstract: The Karakoram Mountains are well known for their widespread surge-type glaciers and slight glacier mass gains. Glaciers serve as sensitive indicators of climate change, adjusting their area and thickness in response to climatic variations. Simultaneously, glaciers provide essential freshwater resources for agricultural irrigation and hydroelectric generation in downstream areas of the Shaksgam River Basin (SRB) in western China. Climate change-induced glacier shrinkage can significantly affect the security and sustainable development of regional water resources. In this study, we analyzed glacier area changes from 2000 to 2016 in the SRB using Landsat TM (Thematic Mapper)/ETM+ (Enhanced Mapper Plus)/OLI (Operational Land Imager) imagery. Our results show that the SRB contained 472 glaciers covering an area of 1840.3 km² in 2016. Glacier area decreased by 0.14%/a since 2000, with the most pronounced shrinkage occurring on southeast-, east-, and south-facing slopes, while northeast- and north-facing slopes experienced the least reduction. Debris-covered areas accounted for 8.0% of the total glacier area. We estimated elevation and mass changes using the 1 arc-second SRTM (Shuttle Radar Topography Mission) DEM (Digital Elevation Model) from 2000 and the 8 m resolution HMA (High Mountain Asia) DEM from 2016. The results indicate an average thickness change of 0.08 (± 0.03) m/a, representing a slight mass increase of 0.06 (± 0.02) m w.e./a since 2000. We found that thinning was significantly less on clean ice compared to debris-covered ice. Additionally, glacier surface elevation changes exhibited strong spatial heterogeneity, with mass accumulation dominating at high altitudes and mass loss occurring primarily at low altitudes, excluding surge-type glaciers. For surge-type glaciers, mass may transfer rapidly from the reservoir to the receiving area during surges, resulting in glacier terminus advance. The main surge mechanism remains unclear, and notably, surging did not increase overall glacier mass in this study.

Keywords: glacier; mass balance; SRTM DEM; HMA DEM; Karakoram Mountains

1 Introduction

Glacier mass balance plays a prominent role in studying the impacts of climate change on glaciers and their responses to climatic variations. Local climate determines the mass and energy supply and loss at glacier surfaces, thereby controlling glacier mass balance. Measurements of glacier mass balance began in the Alps and Scandinavia in the 1940s. In China, such measurements commenced in 1959 with the establishment of the Tianshan Glaciological Station, Chinese Academy of Sciences. To date, continuous mass balance records exceeding 20 years exist for Urumqi Glacier No. 1, Qiyi Glacier, and Dongkemadi Glacier in China [?, ?, ?, ?, ?]. The traditional glaciological method employs stakes or snow pits to obtain point mass balance measurements by tracking stake height changes and snow pit characteristics, which can then be extrapolated to derive glacier-wide mass balance [?, ?]. While glaciological mass balance measurements are highly accurate, glaciers are typically located in uninhabited high mountain regions, making stake or snow pit measurements time-consuming, labor-intensive, and costly. Consequently, the number of glaciers monitored through this method is very limited, and traditional approaches have limitations for assessing glacier mass balance at the basin scale. With the gradual enrichment of remote sensing data for detecting glacial properties, research on glacier changes using remote sensing data has flourished.

The Karakoram Mountains contain substantial ice volumes, and glacier meltwater provides freshwater for many important inland rivers (e.g., the Yarkant River and Hetian River, both tributaries of the Tarim River), representing a critical component of water resources in western China. According to the Fifth Assessment Report of the IPCC (Intergovernmental Panel on Climate Change), Earth's average surface air temperature increased by 0.89°C over the past 100 years (1901–2012) [?, ?]. Climate warming accelerates glacier melting, threatening local livelihoods and contributing to sea-level rise [?, ?, ?]. In the context of global warming, most of the world's glaciers have experienced mass losses. However, many studies have shown that Karakoram glaciers have maintained a balanced or slightly positive mass balance trend over the past decade [?, ?, ?, ?], which may have fostered stable or advancing glacier termini [?, ?, ?, ?]. This phenomenon is termed the “Karakoram Anomaly” [?, ?].

Gardelle et al. (2012a) reported a glacier mass balance of $0.11 (\pm 0.22) \text{ m w.e. / a}$ for the Karakoram Mountains (5615.0 km^2) during 2000–2008 using SRTM DEM and SPOT5 stereo image pair data (density: 900 kg/m^3). Kbetal. (2012) further reported a mass balance of $-0.21, 750.0 \text{ km}^2$ during 2003–2008 using ICESat laser altimetry (density: 900 kg/m^3). Rankland and Braun (2016) demonstrated a mass balance of -1107.0 km^2 for 2000–2012 using TanDEM-X and SRTM/X-SAR DEM data (density: 850 kg/m^3).

Another study using ICESat [?, ?] and ASTER DEMs from 2000 to 2016 [?, ?] showed that the Karakoram Mountains, located on the western edge of the West Kunlun Mountains, represent a larger mass-balance anomaly within the western Tibetan Plateau. These results indicate that Karakoram glaciers have maintained a relatively stable state, although values vary slightly among studies.

To address data scarcity, we updated glacier boundary data for the SRB (Shaksgam River Basin) from 2000 to 2016. A geodetic method based on DEM differencing between SRTM and HMA data was used to determine glacier mass balance changes during different periods. We examined the role of debris cover in glacier mass changes and, combined with previous studies, analyzed the characteristics of surge-type glaciers and climatic factors influencing glacier changes.

2 Study Area

The SRB (35°55'–36°49' N, 75°35'–77°30' E) is located on the northern slope of the Karakoram Mountains in western China (Fig. 1 [Figure 1: see original paper]). The Shaksgam River, the main river in the SRB, originates from the Karakoram Mountains at Shenglinandaban and flows into the Yarkant River at Cha Hekou. The river course initially runs east-west, gradually shifts to southeast after 30 km, and finally returns to an east-west direction in its last 40 km [?, ?]. This area constitutes the upper source region of the Tarim River and is also known as the “Karakoram Corridor.” The entire valley extends from southeast to northwest, with an average altitude of approximately 5100 m a.s.l. The world’s second-highest peak, Mount Qogir (K2), is the main peak in this region, reaching 8611 m a.s.l.

The SRB is primarily influenced by a continental climate. According to the Second Chinese Glacier Inventory, the SRB contains 491 glaciers (some small glaciers were removed in this study) with a total area of 1884.2 km². The most densely developed glacier area in China is found in the Karakoram Mountains. Eight glaciers have areas exceeding 70.0 km², accounting for 55% of the total glacier area in the study region. The Yengisogat Glacier, with an area of 359.1 km² and length of 42 km, is the largest and longest glacier in China [?, ?, ?]. Due to high altitude and low temperatures, measurement data are scarce. The Karakoram Mountains feature high elevations and steep terrain. Interception of moisture and air masses by high mountains, combined with orographic storage effects, results in greater precipitation at high altitudes than at low altitudes, providing abundant mass sources for glacier formation and thus developing the largest and most concentrated glacier system in the mid-latitudes [?, ?].

Fig. 1 Location of the study area and distribution of glaciers in 2016. The background map is a hillshade of SRTM (Shuttle Radar Topography Mission) DEM (Digital Elevation Model). Debris-covered ice data were obtained from Nico et al. (2018).

3.1 Landsat Data

Landsat images (Table 1) were used to analyze glacier area changes in the SRB, including Landsat TM/ETM+/OLI imagery. Eight high-quality Landsat TM/ETM+/OLI scenes were used in this study, downloaded from the USGS (United States Geological Survey) website (<https://earthexplorer.usgs.gov>). All scenes are orthorectified using SRTM data and ground control points from the

GLS2005 (Global Land Survey 2005) dataset, achieving systematic radiometric and geometric accuracy. Due to the long time span, high resolution, and free availability of Landsat data, it has been widely applied in glacier remote sensing research [?, ?, ?].

Table 1 Remote sensing images used in this study

Satellite sensor	Period of data	Path/Row	Cloud (%)	Spatial resolution (m)
Landsat TM	4 Sep 2000	148/35		15/30
Landsat TM				15/30
Landsat ETM+				15/30
Landsat ETM+				15/30
Landsat ETM+				15/30
Landsat ETM+				15/30
Landsat ETM+				15/30
Landsat ETM+				15/30
Landsat ETM+				15/30
Landsat OLI	24 Sep 2016	148/35		15/30
Landsat OLI				15/30

3.2.1 SRTM DEM

The SRTM mission acquired interferometric synthetic aperture radar (InSAR) data simultaneously in both C-band and X-band frequencies from February 11-22, 2000 [?, ?]. Data were acquired between 56°S and 60°N, covering 80% of Earth's land surface [?, ?]. The 1 arc-second (30 m) SRTM C-band data have a linear vertical absolute height error of less than 16 m and a linear vertical relative height error of less than 10 m (at 90% confidence level). The SRTM DEM can be referenced to the glacier surface from the last balance year (1999), with slight seasonal variation [?, ?]. The C-band exhibits some penetration into ice and snow, while the X-band shows less penetration. However, because the X-band swath width (50 km) is smaller than the C-band swath width (225 km) [?, ?], only 35% of SRB glaciers are covered by X-band DEM. Low signal and signal-to-noise ratio issues result in voids in SRTM DEM data, but these affect only 4% of the total glacier area in this study. Therefore, the 1 arc-second, non-void-filled SRTM C-band DEM was used to estimate glacier surface elevation changes after the 1999 ablation period. These data are freely available from <http://earthexplorer.usgs.gov/>.

3.2.2 HMA DEM

The HMA DEMs were generated from high-resolution along- and cross-track stereo images from DigitalGlobe satellites, with a resolution of 8 m, collected from January 28, 2002, to November 24, 2016. The HMA DEM

comprises more than 4000 strips with a width of 13.1 km and length of 17.4 km, which reduces errors and eliminates seams. In this study, six images (100 km \times 100 km) from 2015–2016 were collected. The HMA DEM can be referenced to the glacier surface from the last balance year (2016). Although the HMA DEM suffers from data voids, it is otherwise of very high quality (Fig. 2 [Figure 2: see original paper]), with voids affecting only 5% of the total glacier area. The data were downloaded free from https://nsidc.org/data/HMA_{{DEM8m}}_{{MOS}}/versions/1.

Fig. 2 Resolution comparison of the two DEMs. (a) The 1 arc-second SRTM DEM from 2000; (b) The 8 m HMA (High Mountain Asia) DEM from 2015. The white spots in (b) are voids. The black outlines indicate glacier areas, and both images are from Paul et al. (2019).

4.1 Glacier Boundary Delineation

Accurate glacier boundary information is essential for determining mass balance changes. We selected scenes from the ablation season (June to September, primarily August) to minimize snow cover effects and comprehensively considered acquisition timing and cloud cover (Table 1). Seasonal snow and clouds can be distinguished by comparing glacier body images from adjacent years.

Due to its simplicity and accuracy, the band ratio method is most suitable for extracting glacier boundaries [?, ?, ?]. We applied a band ratio threshold method (TM3/TM5 for TM/ETM+ and TM4/TM6 for OLI), using a threshold of 1.9 for this task. This method exploits the strong reflectivity of glaciers in visible light bands and strong absorption in near-infrared bands to differentiate glacierized from non-glacierized surfaces. However, this approach may misclassify proglacial lakes as glaciers [?, ?], an error easily corrected through visual interpretation.

Glacier surfaces in the study area are covered by debris and supraglacial boulders, making identification of these features time-consuming yet crucial for post-processing. Several principles guide debris-covered glacier identification. For example, Kääb (2005) suggested that areas with slopes below a threshold (23°) and directly connected to clean ice can be considered debris-covered ice. The surface moraine color on glaciers differs from debris on the glacier's outer edge, and supraglacial boulders across a glacier tongue exhibit similar spectral characteristics. With increasing air temperature, the glacier tongue shape shows obvious decreases, which can be identified. These principles enable identification of supraglacial boulders and debris-covered ice. The extraction process also utilized the second Chinese Glacier Inventory (<http://westdc.westgis.ac.cn/>) and Google Earth.

Despite extensive efforts to improve the accuracy of extracted glacier boundaries, errors persist for various reasons, necessitating uncertainty assessment. This study employed the method proposed by Jin et al. (2005) to evaluate glacier boundary errors. First, buffer zones were analyzed for glacier boundaries ex-

tracted from TM, ETM+, and OLI images (using half the image resolution as buffer distance; thus, TM, ETM+, and OLI images have a 15 m buffer distance). The glacier area within the buffer zone was then compared to the area extracted from the original image, with the ratio between the difference and the original area representing the uncertainty in glacier area extraction. Results showed uncertainties of $\pm 3.72\%$ and $\pm 3.54\%$ for extracted glacier boundaries in 2000 and 2016, respectively, both within ranges reported in previous studies [?, ?].

4.2 Geodetic Mass Balance Calculations

We employed the geodetic method to obtain glacier surface elevation changes by comparing DEM data from different periods and then estimated glacier mass balance by incorporating glacier area and density [?, ?, ?].

$$B = \frac{\rho_i}{M \cdot S_g} \sum_{i=1}^M \Delta h_i \cdot S_p$$

where B is glacier mass balance (m w.e.); ρ_i is ice density (kg/m^3); S_g is glacier area (km^2); M is the number of pixels within the glacier boundary; Δh_i is glacier surface elevation difference (m); and S_p is pixel size (m), representing the spatial resolution of the DEM data.

4.3 Co-registration and Correction of DEMs

Due to differences in DEM acquisition systems, geodetic reference planes, and processing methods, horizontal and vertical offsets may exist between the SRTM DEM and HMA DEM. Even small horizontal shifts can cause significant elevation errors in mountainous terrain. Therefore, relative registration of each DEM dataset is required before estimating glacier surface elevation changes. We applied the method proposed by Nuth and Kääb (2011), which demonstrates a cosine-curve relationship between elevation differences, aspect, and slope [?, ?] (Fig. 3a [Figure 3: see original paper]), enabling statistical correction of relative vertical and horizontal distortions between the SRTM DEM and HMA DEM.

Based on the SRTM DEM, the HMA DEM was resampled to 30 m spatial resolution. Using ArcGIS 10.2.2 software, a difference map was created between the SRTM C-band DEM and HMA DEM. Based on statistical analysis, 5% and 95% quantile thresholds were applied to eliminate outliers near DEM edges and data gaps [?, ?]. Cosine fitting yielded translation vectors, and the HMA DEM was shifted to achieve image registration. The calculations follow Eqs. 2-6. Additionally, based on the relationship between elevation difference and maximum curvature in non-glacier regions (Fig. 3b), biases caused by different spatial resolutions between the two datasets were refined for both glacier and non-glacier areas [?, ?]. Before adjustment, the mean elevation difference and standard deviation in non-glacier regions were -19.83 m and 14.91 m, respectively. After correction, the elevation difference in non-glacier regions centered on a mean of

-0.38 m, with standard deviation reduced to 11.8 m. These corrections stabilized the non-glacier regions, making the DEMs suitable for estimating glacier mass balance changes.

$$dh = \tan(\alpha) \cdot (a \cdot \cos(b - \phi) + c)$$

$$\bar{d}h = \tan(\bar{\alpha}) \cdot c$$

where dh is individual elevation difference (m); α and ϕ represent pixel slope and aspect ($^{\circ}$), respectively; $\bar{d}h$ is overall elevation bias between SRTM DEM and HMA DEM (m), representing vertical offset; a is horizontal shift magnitude (m); b is shift vector direction ($^{\circ}$); c is mean bias between DEMs divided by mean slope tangent (m); and $\bar{\alpha}$ is average DEM slope ($^{\circ}$).

Offsets in the x (m), y (m), and z (m) directions between the two DEMs can be calculated as:

$$\Delta x = a \cdot \sin(b)$$

$$\Delta y = a \cdot \cos(b)$$

$$\Delta z = c \cdot \tan(\bar{\alpha})$$

where a , b , and c are obtained through cosine fitting.

Fig. 3 (a) Scatter plot of aspect vs. slope for standardized elevation differences in non-glacier areas. (b) Relationship between elevation difference and maximum curvature in non-glacier areas of the SRB (Shaksgam River Basin).

4.4.1 Evaluation of Elevation Change Uncertainty

The root mean square error or standard deviation of elevation residuals between different DEMs in areas away from glaciers can estimate the uncertainty of elevation changes [?, ?].

$$E_{\sigma} = \frac{SD_{\text{no glac}}}{\sqrt{N}}$$

$$E = \sqrt{E_m^2 + E_{\sigma}^2}$$

where E_{σ} is average elevation bias off glaciers (m); $SD_{\text{no glac}}$ is standard deviation in non-glacial areas (m); N is number of measurement points; E_m is

average elevation difference in non-glacier areas (m); and E is elevation change error (m).

To calculate E_σ using a reasonable number of pixels near glaciers, we only used pixels within a 5 km buffer zone around glaciers. Note that DEMs exhibit strong spatial autocorrelation in elevation values of adjacent grids. To reduce autocorrelation effects, a decorrelation length based on spatial resolution is recommended. For DEMs with 30 m spatial resolution, 600 m is appropriate as the decorrelation length [?, ?].

Table 2 Statistical results of vertical error before and after adjustment of HMA (High Mountain Asia) and SRTM (Shuttle Radar Topography Mission) DEMs (Digital Elevation Models) in non-glacier areas

Parameter	Before co-registration	After co-registration
E_m (m)		
$SD_{\text{no glac}}$ (m)		
E_σ (m)		
E (m)		

Note: E_m , average elevation difference in non-glacier areas; $SD_{\text{no glac}}$, standard deviation in non-glacier areas; N , number of measurement points; E_σ , average elevation bias off glaciers; E , error of elevation change.

4.4.2 Effect of SRTM Penetration

The SRTM C-band (5.7 GHz) exhibits some penetration into ice and snow, with penetration depths between 1 and 10 m [?, ?]. SRTM X-band (9.7 GHz) penetration is expected to be lower than C-band (a hypothesis requiring confirmation [?, ?]). We consider the elevation difference (SRTM C-band – SRTM X-band) as a first approximation of C-band radar penetration over glaciers [?, ?]. Here, we estimated penetration by differencing SRTM C-band and X-band DEMs. The X-band and C-band data were acquired simultaneously, eliminating elevation changes from ablation or accumulation [?, ?, ?, ?]. Before estimating SRTM C-band penetration depth, the SRTM X-band and C-band DEMs were co-registered and corrected. The final mean SRTM C-band penetration depth over the SRB was approximately 2.8 m, consistent with Gardelle et al. (2013), who reported a penetration depth of 3.4 m.

4.4.3 Density Assumption Error

Converting ice volume to mass is a critical step when estimating glacier mass changes using the geodetic method [?, ?]. Glacier density must be considered to convert elevation changes to mass balance changes. Fresh snow, firn, and ice exhibit substantial density differences, with glacier

densities ranging from 100 to 917 kg/m³ [?, ?]. The density parameter value introduces 5%-6% uncertainty in glacier-scale mass balance estimates [?, ?]. In the Karakoram Mountains, parameters for converting glacier elevation changes to mass changes are assumed to follow Sorge's law [?, ?], meaning glacier density remains constant vertically. Using 900 kg/m³ as the density conversion parameter yielded a mass balance of 0.11 (±0.22) m w.e./a during 1999–2008. Assuming a glacial density of 600 kg/m³ in the accumulation zone reduces the mass balance to 0.05 (±0.16) m w.e./a, though both the extreme density scenario was used as the volume-to-mass conversion parameter.

4.4.4 Accuracy of Glacier Boundary

Glacier area uncertainty refers to errors caused by differences in S_g and M in Equation 1 when estimating mass balance. To reduce this error, the maximum glacier area after merging two periods can be used when calculating glacier volume changes. When calculating glacier mass balance, the union of glacier boundaries from both periods can be employed [?, ?, ?, ?]. We obtained final glacier areas of 1884.2 km² in 2000 and 1840.3 km² in 2016.

4.4.5 Uncertainty of Mass Balance

Final mass balance uncertainty was determined using estimated uncertainties in glacier area, elevation changes, and glacier density uncertainty of 60 kg/m³:

$$E_{MB} = \sqrt{\left(\frac{E \cdot \rho_i}{t \cdot \rho_w}\right)^2 + \left(\frac{\Delta\rho \cdot \Delta h}{t \cdot \rho_w}\right)^2}$$

where E_{MB} is mass balance uncertainty (m w.e./a); t is observation period; ρ_i is ice density (850 kg/m³); $\Delta\rho$ is ice density uncertainty (60 kg/m³); and ρ_w is water density (999.92 kg/m³) [?, ?].

5.1 Area Changes

In 2016, the SRB contained 472 glaciers with a total area of 1840.3 km² (Fig. 4 [Figure 4: see original paper]). Large glaciers (> 1 km²) dominate in terms of area (94.3%) and dominate in number (70.6% of total count) (Fig. 4a). Glacier surface slopes in the SRB range approximately 16°–34°, covering 95.6% of the total glacier area. Glaciers with north, northeast, northwest, or east aspects account for 63.2% of the total area. Glacier shrinkage was most pronounced on southeast, east, and south aspects, while west, northeast, and north aspects showed the least reduction (Fig. 4b).

Fig. 4 Glacier distribution and change in the SRB. (a) Area and number of 2016 glaciers in different size classes; (b) Distribution of glacier area by aspect in 2000 and 2016; (c) Change in glacier area and area reduction rate under

different size classes from 2000 to 2016; (d) Distribution of glacier area with elevation in 2016.

Glaciers in the SRB are significantly debris-covered, with debris-covered glacier distribution shown in Figure 1. The total debris-covered area was 146.5 km². Among all debris-covered glaciers, 20 had debris-covered areas larger than 1.0 km². The Yengisogat Glacier has the most extensive debris cover in the SRB (32.9 km², about 9.3% of its area). Approximately 86.2% of the debris-covered area lies in the 4200–5200 m altitude range, 10.7% is above 5200 m, and only 3.1% is below 4200 m.

Comparing glacier areas between 2000 and 2016, the total area reduction was 43.9 km², with an average annual shrinkage rate of 0.14%/a. Small glaciers shrank significantly, but large glaciers contributed most to absolute area loss (Fig. 4c). Approximately 91.5% of the total glacier area lies between 4400 and 6300 m, while only 1.6% is below 4400 m and 6.2% is above 6300 m. The median elevation is about 5682 m (Fig. 4d). Topographic analysis shows that glacier area below 4000 m has disappeared completely (0.3 km²). Low-altitude glaciers vanished while high-altitude glaciers changed little and did not disintegrate, causing a decrease in total glacier number. Glaciers in the SRB experienced weakening area shrinkage from 2000 to 2016.

5.2 Elevation and Mass Changes

Glaciers in the SRB exhibited weak surface thickening from 2000 to 2016. Glaciers covering 1862.3 km² (the union of 2000 and 2016 glacier extents) experienced thickening of 1.21 (± 0.41) m ($0.08 (\pm 0.03)$ m/a). Using 850 (± 60) kg/m³ as the density parameter, glacier mass gain was 0.06 (± 0.02) m w.e./a. Glacier surface mass distribution is uneven (Fig. 5 [Figure 5: see original paper]), showing mass accumulation dominating at high altitudes and mass loss occurring at low altitudes (excluding surge glaciers). The Yengisogat Glacier is typical, showing obvious thickening in the upper reaches of the north ice flow (A in Fig. 5a), upper reaches of the northwest ice flow (B in Fig. 5a), and the middle part of the main stream (C in Fig. 5a).

Fig. 5 Changes in glacier surface elevation in the SRB from 2000 to 2016. Glacier boundaries are based on the union of 2000 and 2016 glacier areas. Surge-type glaciers and those in post-surge or quiescent phases during 1999–2011 were reported by Gardelle et al. (2012a, 2013).

6.1 Comparison with Previous Studies

Previous studies agree that Karakoram glaciers have maintained a weak positive or stable mass balance since 2000 (Table 3). Gardelle et al. (2013) found thickening of 0.12 (± 0.19) m/a from 2000 to 2011 based on SRTM and SPOT5 DEMs. Rankl and Braun (2016) reported thickening of 0.07 (± 0.04) m/a (2003–2008) using SRTM and ICESat. X and SRTM/X–SAR. K betal. (2012) found thinning of 0.07 (± 0.04) m/a (2003–2008) using SRTM and ICESat. band penetration result in different thickness values. K betal. (2012) used a mean SRTM C–

band penetration of $2.4(\pm 0.3)$ m for the Karakoram Mountains, less than 3.0 m (snow and ice), 8.0 m (accumulation) of glaciers [?, ?]. Glacier characteristics differ across eastern, western, and central Karakoram regions. Gardelle et al. (2013) focused on the central Karakoram, while Kääh et al. (2012) covered the entire Karakoram Mountains; our study area lies mainly in the eastern and central Karakoram. Additionally, differences in DEMs, snow/ice density, and glacier boundaries may explain some discrepancies. Previous studies estimated average penetration depths of 2.7 m in the Karakoram Mountains [?, ?], 2.8 m in the West Kunlun Mountains, 1.9 m in the Pamir [?, ?], 3.5 m in the Hindu Kush, and 2.0–3.0 m in the Karakoram Mountains [?, ?]. Our penetration depth of 2.8 m agrees with previous studies and is considered acceptable and suitable for estimating glacier elevation changes in the SRB. These studies suggest that average glacier surface elevation changes in the Karakoram Mountains are relatively small, with glaciers experiencing stable conditions.

Table 3 Comparison of mass balance budgets in this study and others

Region	Study period	Elevation change (m/a)	Mass balance (m w.e./a)	Reference
Karakoram Mountains	2003–2008	-0.07 (± 0.04)	-0.06 (± 0.04)	Kbetal.(2012) Karakoram Mountains Gardner

Note: - indicates no data available.

6.2 Debris-Covered Ice and Clean Ice

Debris-covered areas account for about 8.0% of total glacier area (Fig. 6a [Figure 6: see original paper]). Ice cliffs, heterogeneous debris cover, and supraglacial lakes contribute to complex mass-loss patterns on debris-covered tongues [?, ?]. While thick debris cover generally acts as a protective insulating layer [?, ?], previous studies report accelerated melt when debris thickness falls below a critical value [?, ?, ?]. In this study, debris cover positively influenced ablation, with melt noticeably smaller on clean ice than on debris-covered ice at 4000–5900 m altitude during 2000–2016 ($-0.63 (\pm 0.03)$ vs. $0.13 (\pm 0.03)$ m/a) (Fig. 6b). Similar results have been found in the Karakoram Mountains [?, ?], eastern Pamir [?, ?], and central Nyainqentanglha Range [?, ?].

Fig. 6 Distribution of glacier area in 2016 (a) and glacier surface elevation changes during 2000–2016 (b) at 100-m elevation intervals in the SRB for debris-covered ice and clean ice.

6.3 Surge-Type Glaciers

According to previous studies, at least 12 locations in this basin have experienced surges (Fig. 5). Most surges occurred between 2000 and 2016 [?, ?, ?], with

one (location C in Fig. 5a) occurring during 2011–2016. During 1999–2011, location C was in a post-surge or quiescent phase, indicated by a dashed black box. We found obvious thickening at location C, accompanied by thinning in the upper reaches (below A and B in Fig. 5a), consistent with surge-type glacier characteristics. While we cannot determine the exact timing of the surge, previous studies indicate that location C on the Yengisogat Glacier had a rapid movement velocity of 900 m/a from June to August 2012, which then decreased rapidly, suggesting this period may represent the surge peak [?, ?].

Most glaciers in the Karakoram Mountains have either stable terminus locations or have been advancing, partly due to increased local precipitation [?, ?] and partly due to glacier surging [?, ?]. Here, glacier surging did not increase overall glacier mass. Generally, rapid mass transfer to receiving areas results in glacier terminus advance, though this is not always the case. While some Karakoram glacier surge characteristics resemble thermally controlled surges elsewhere (e.g., Svalbard), the main surge mechanism remains unclear [?, ?].

6.4 Analysis of Factors Contributing to Glacier Anomaly

Glaciers are comprehensive products of climate, topography, and other factors. Since terrain has remained unchanged for decades or even centuries, glaciers are sensitive to climate change [?, ?]. Potential explanations such as cloud cover, precipitation, and temperature may drive Karakoram glacier changes. Based on global meteorological reanalysis and station data, Forsythe et al. (2015) and Bashir et al. (2017) reported increased cloudiness in the Karakoram Mountains. Increased cloud cover may reduce incoming shortwave radiation [?, ?], which is generally considered the primary energy source for glacier mass changes [?, ?]. Additionally, previous studies report that increased cloud cover leads to increased precipitation [?, ?, ?]. Karakoram climate is primarily influenced by westerly circulation and the Tibetan anticyclone [?, ?]. Cannon et al. (2015) reported increased frequency and intensity of westerly-dominated precipitation in recent years, which appears to cause slight increases in winter snowfall in the Karakoram [?, ?]. Precipitation change is considered a powerful control on glacier mass balance in the Karakoram Mountains [?, ?, ?]. Moreover, summer cooling has been a particularly important driving factor for glacier mass balance in the Karakoram Mountains in recent decades [?, ?, ?]. It is worth noting that tree-ring chronologies do not provide evidence that Karakoram temperatures differ from other High Mountain Asia regions.

7 Conclusions

This study examined glaciers in the SRB, extracting glacier boundaries for 2000 and 2016 from Landsat TM/ETM+/OLI imagery. Based on HMA DEM and SRTM DEM data, we estimated surface elevation and mass balance changes from 2000 to 2016.

We found that the SRB contained 472 glaciers with a total area of 1840.3 km²

in 2016. Glacier area decreased by 43.9 km², with an average annual shrinkage rate of 0.14%/a, primarily in southeast, east, and south directions, during 2000–2016. Compared with mountain glacier melt in western China and globally, SRB glaciers experienced only slight shrinkage. The debris-covered area was 146.5 km², accounting for about 8.0% of the total area.

Glacier thickness showed a weak increasing trend, with thickening of 0.08 (± 0.03) m/a, or 0.06 (± 0.02) m w.e./a. Thinning was significantly greater on debris-covered ice than on clean ice at 4000–5900 m altitude between 2000 and 2016 in the SRB ($-0.63 (\pm 0.03)$ vs. $0.13 (\pm 0.03)$ m/a). Results show that glacier mass transferred rapidly from reservoir to receiving areas, resulting in glacier terminus advance, though not universally.

Acknowledgements This work was supported by the Second Tibetan Plateau Scientific Expedition and Research Program (2019QZKK0201), the Strategic Priority Research Program of the Chinese Academy of Sciences (XDA20060201, XDA20020102), the National Natural Science Foundation of China (41761134093, 41771077, 42001067), the State Key Laboratory of Cryosphere Science funding (SKLCS-ZZ-2019), and the National Science and Technology Basic Resources Survey Program of China (2019FY100202).

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