Spring Mass Balance on Shodug Glacier

2022-2024

Cryosphere Services Division
National Center for Hydrology and Meteorology
2024

List of acronyms:

- HKH – Hindu Kush Himalaya
- WGMS – World Glacier Monitoring Service
- WMO – World Meteorological Organization
- MSI – Multispectral Instrument
- RTK – Real-Time Kinematic
- GNSS – Global Navigation Satellite System
- mm w.e. a^{-1} – Millimeter Water Equivalent per Annum
- DEM – Digital Elevation Model
- IDW – Inverse Distance Weighting
- AGMB – Annual Glacier Mass Balance
- CGMB – Cumulative Glacier Mass Balance
- ICIMOD – International Centre for Integrated Mountain Development
- TCS7 – Trimble Controller Series 7
- WGS 84 – World Geodetic System 1984
- CSV – Comma-Separated Values
- IPCC – Intergovernmental Panel on Climate Change
- UNESCO – United Nations Educational, Scientific and Cultural Organization
- Gt – Gigatonnes
- m.a.s.l. – meters above sea level

Executive Summary

This technical report provides a comprehensive analysis of the mass balance and terminus dynamics of the Shodug Glacier, a designated benchmark glacier situated in Bhutan, monitored from 2022 to 2024 using geodetic methods, specifically differential GPS (dGPS) technology. The Shodug Glacier, crucial for regional hydrological systems and hydropower infrastructure, was evaluated through detailed field measurements, supported by satellite imagery and advanced spatial analysis techniques. Data acquisition included precise surface elevation measurements using RTK GNSS technology, with elevation differences processed through ArcGIS and interpolation techniques such as Inverse Distance Weighting (IDW). These methodologies facilitated the construction of accurate digital elevation models (DEMs), enabling reliable determination of glacier surface changes and terminus recession.

The findings highlight a pronounced negative mass balance for Shodug Glacier, registering a significant loss of -1897.6 mm water equivalent annually over the studied period, underscoring accelerated melting predominantly at lower altitudes. Additionally, a notable terminus retreat of approximately 48.62 m was documented, reflecting the ongoing climatic stress and warming trends within the Himalayan region. This mass loss is consistent with broader regional and global observations, emphasizing the critical need for continued monitoring and adaptive management strategies. The study's robust uncertainty analysis, accounting for altitudinal variability, boundary delineation accuracy, and assumed ice density variations, reinforces the reliability of its findings, providing a crucial baseline for climate impact assessments and long-term water resource management planning in Bhutan and the broader Hindu Kush Himalaya region.

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1.Introduction

Mountain glaciers are the visual evidence of climate change. Their widespread retreat over the past century has contributed significantly to global sea-level rise and altered regional hydrological regimes. In response to the accelerating cryosphere crisis, the global scientific community officially established World Glacier Day on March 21st, 2025. This initiative seeks to raise awareness of the rapid glacier retreat occurring across all continents and its cascading consequences for water security, sea-level rise, and climate stability. It also underscores the urgency of sustained glacier monitoring and coordinated climate action, as glaciers continue to lose mass at unprecedented rates (WGMS, 2023; Zemp et al., 2015).

Scientific observations consistently confirm the magnitude and acceleration of glacier mass loss over recent decades. Glaciers have been retreating since the early 20th century across most mountain regions (DeBeer et al., 2020; IPCC, 2023), with significantly increased rates in the 21st century (Zemp et al., 2019). Hugonnet et al. (2021) reported that nearly all mountain glaciers are now out of balance with the current climate, losing an average of 267 ± 16 gigatonnes (Gt) of ice annually between 2000 and 2019. Complementing these findings, a 2025 UNESCO report estimates that over 9,000 Gt of ice have been lost since 1975—an amount equivalent to an ice blocks the size of Germany and 25 meters thick. Similarly, data from the World Glacier Monitoring Service (WGMS) show an average annual loss of 273 Gt of glacier mass (excluding Greenland and Antarctica) since 2000. WGMS Director Michael Zemp contextualized this figure by noting that it equals the global population's total freshwater use over a 30-year period.

Looking forward, the outlook remains deeply concerning. According to the World Meteorological Organization (WMO), if greenhouse gas emissions are not rapidly curtailed, up to 80% of the world's small glaciers—particularly those in Europe, East Africa, and parts of Asia—could disappear entirely by the end of this century. The loss of these glaciers would have severe implications for regional water availability, disaster risk, and ecological stability.

The Himalayan region, including Bhutan, reflects these global patterns. Situated within the broader Hindu Kush Himalaya (HKH)—a region warming faster than the global average—Bhutan's glaciers are undergoing marked retreat and thinning. According to the Bhutan Glacier Inventory 2018, the country hosts around 700 glaciers, covering approximately 629.55 km^2, or

1.64% of its total land area. Glacier monitoring by the National Center for Hydrology and Meteorology (NCHM) has revealed widespread evidence of negative mass balance and terminus retreat, particularly in Bhutan's benchmark glaciers.

Bhutan's glacier monitoring program has evolved significantly over the past two decades. The first systematic documentation was carried out through the Inventory of Glaciers and Glacial Lakes (Mool et al., 2001), coordinated by ICIMOD. The first in situ mass balance study was conducted on the Gangju La Glacier by Tshering and Fujita (2016), marking a milestone in Bhutan's cryosphere research. Their decade-long study (2003–2014) applied traditional glaciological methods, such as stake measurements, and revealed a consistent and significant negative mass balance, highlighting the vulnerability of Bhutan's glaciers to climatic shifts (Tshering & Fujita, 2016).

Since then, Bhutan has expanded its cryosphere observations through a combination of remote sensing and in situ methods. As part of its national cryosphere strategy, NCHM has designated three benchmark glaciers, Gangju La, Thana, and Shodug for annual mass balance monitoring and long-term studies.

Among these, the Shodug Glacier, located at the headwaters of the Thim Chhu, was identified as a benchmark glacier in 2022 (NCHM, 2023). It plays a vital hydrological role, providing seasonal meltwater to downstream communities and contributing to the base flow of Bhutan's first major hydropower plants, Chukha and Tala. This glacier is of particular interest for assessing climate-driven changes in both cryospheric and hydrological regimes.

Benchmark or reference glaciers, like Shodug, are crucial to global glacier monitoring programs due to their high-resolution, long-term datasets. These glaciers serve as indicators of climate forcing on the cryosphere and act as ground truth for scaling up to regional and global analyses (Zemp et al., 2009; Braithwaite, 2002). Traditional glaciological methods, involving direct measurements of snow accumulation and ice ablation, remain central to estimating specific mass balance (Cogley & Adams, 1998; Dyurgerov & Meier, 1997). However, these are increasingly supplemented by geodetic methods, including satellite and dGPS-based elevation change analysis, to enhance spatial coverage and accuracy (Cogley, 2009; WGMS, 2023).

This integrated approach is essential for capturing glacier changes at different temporal and spatial scales. Combined glaciological and geodetic data have shown that glaciers contributed roughly 21–25% of observed sea-level rise between 2003 and 2009 (Gardner et al., 2013; Zemp et al., 2019). Establishing Shodug as a benchmark glacier enhances Bhutan's contribution to international glacier monitoring networks and provides crucial data for understanding the region's response to climate change (Gärtner-Roer et al., 2019).

This technical report presents an assessment of the mass balance of the Shodug Glacier from 2022 to 2024, using differential GPS (dGPS) techniques. The findings contribute to a growing body of knowledge on glacier-climate interactions in the eastern Himalaya and provide essential input for long-term water resource planning in Bhutan.

2.Aim and Objective

The primary aim of this study is to measure glacier mass balance and terminus position of Shodug glacier through geodetic method, thereby contributing to Bhutan's long-term glacier monitoring and climate adaptation efforts.

3.Study Area

3.1 Location

A clean type Shodug Glacier is located in WGS 84/UTM zone 45N of Bhutan at 27.940 N, 89.950 E (Fig.1) with an approximate area of 3.71 km^2 (NCHM Annual report, 2023). It extends from an elevation of 5100 to 5500 m.a.s.l.

3.2 Accessibility

This route can be accessed via Thimphu-Barshong-Shodug, which takes three days on foot to reach the study site. It takes almost 2 hours for an average person to reach the study site from the basecamp.

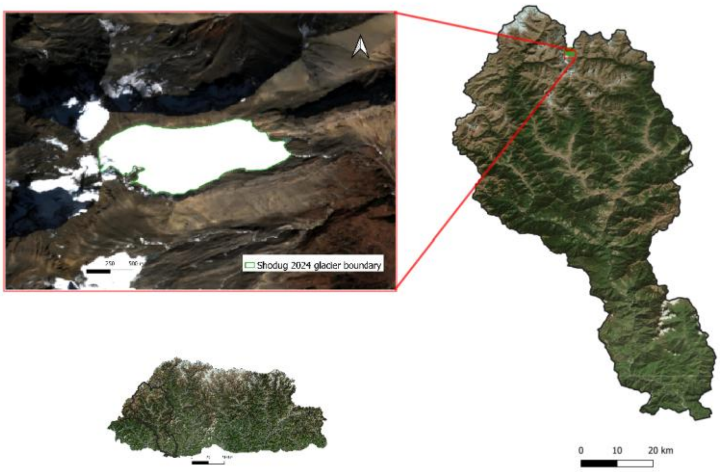

Figure 1: Location of Shodug at the headwaters of Thim Chu within the Wangchu basin (outlined in black). The background is a Sentinel-2 True Color Composite.

4. Data and Methodology

4.1 Data Acquisition

During the field expedition, glacier surface elevation data were collected using RTK GNSS (Trimble R10-2). Prior to the survey, Trimble R10-2 was calibrated for higher precision to avoid errors. The base station was set up accurately on the previously marked point (Fig.2b), which is at a certain distance away from the glacier snout and kept at the height of 2m from the ground. Manually inserting the known coordinate of base station in TCS7 controller of Trimble R10-2, base station was set to start for the collection of data. A rover was mounted on a backpack and the height of the rover from the ground was measured and entered in the controller accordingly. The logging distance of 1m with a logging interval of one second was set for all survey profiles in continuous Topo mode. Glacier surface elevations data were collected (Fig.2a) by walking across the glacier following the survey track file (shape file) of the previous year. Several new points were collected for future reference.

Similarly, glacier terminus data were collected by walking on the glacier, following the snout of the glacier for that given point of time. Unlike glacier surface elevations, there is no reference to previous year's data to walk through it. Glacier terminus either advance or recede-in most cases they recede. Therefore, a profile along the current terminus position is taken by walking along the terminus of the glacier and compared with the previous terminus profile line to determine the changes in terminus position of the glacier.

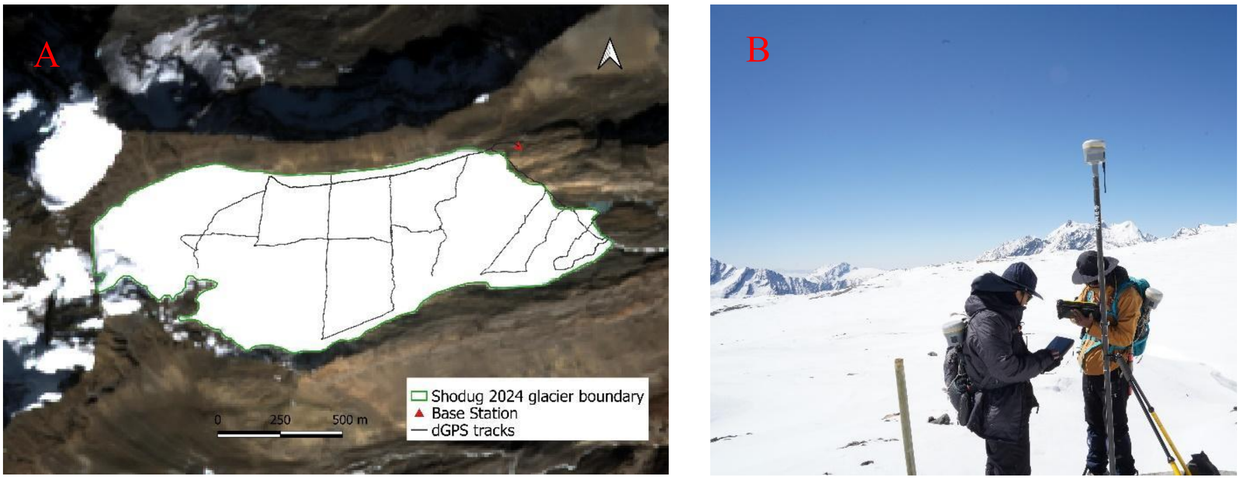

Figure 2: A) dGPS survey tracks. B) Base set up. The background is a Sentinel-2 True Color Composite.

4.2 Data Post Processing

The raw data obtained in Trimble TSC7 were exported in CSV format using the inbuilt software (Trimble Access) in the Trimble TSC7 controller.

The exported CSV file was scrutinized in excel sheet for abnormal data points and then the shape file (.shp) was generated in ArcGIS. Accordingly, the shapefile generated was loaded back to the TSC7 controller to be used the following year while collecting the glacier surface elevation using Trimble R10-2.

This data is integrated to construct 1m Digital Elevation Model (DEM) using inverse distance weighting (IDW) interpolation tool in ArcGIS with a search result of 0.7m, for the year 2022-2024. The difference in DEMs produced in the current year and the previous year with the same reference grid, provides a change in elevation in each grid point (Fig. 3). This difference in DEMs is calculated using the DEM differencing technique of two consecutive years using an incorporated map algebra tool in ArcGIS.

The change in elevation is further filtered in excel sheet and, an average change of elevation i.e. Δh_g for every 50 m altitudinal band was calculated by averaging the available elevation change values. The annual mass balance (geodetic) at a point is calculated following P. Tshering & Fujita 2016 as follows:

$$b_g = \frac{\Delta h_g \rho_i + (S_{t2} - S_{t1})(\rho_s - \rho_i)}{(t2 - t1)}$$

Where b_g is the annual mass balance at a given point by the geodetic method (kg m^{-2} a^{-1} equivalent to mm w.e.a^{-1}); Δh_g is the elevation change (m) obtained from differenced DEMs; ρ_s *and* ρ_i are the density of snow and ice (kg m^{-3}) respectively. S_{t2} *and* S_{t1} are thick of snow (m) for years t1 and t2.

Finally, the area averaged annual mass balance ($\overline{b_g}$; mm w.e.a^{-1}) estimated by:

$$\overline{b_g} = \frac{\sum A_z b_{gz}}{A_T}$$

Where A_z and A_T are glacier areas within 50 m altitude band and total area (m2) respectively. b_{gz} is the average mass balance within the 50 m altitude band. Regarding the area (A_z), we use A_z=$(A_{t1} + A_{t2})/2$, where A_{t1} and A_{t2} represent the areas of the measurements taken in years $t1$ and $t2$ at a given altitude band(m^2), respectively.

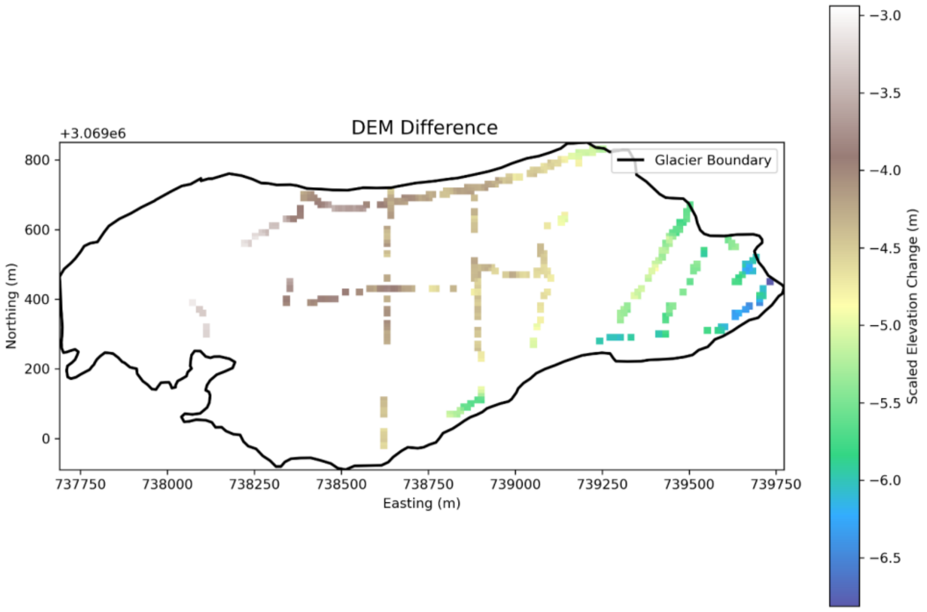

Figure 3:DEM difference calculated for the years 2022–2024. The raster values were resampled using a factor of 10 to enhance visual clarity.

5. Hypsometry

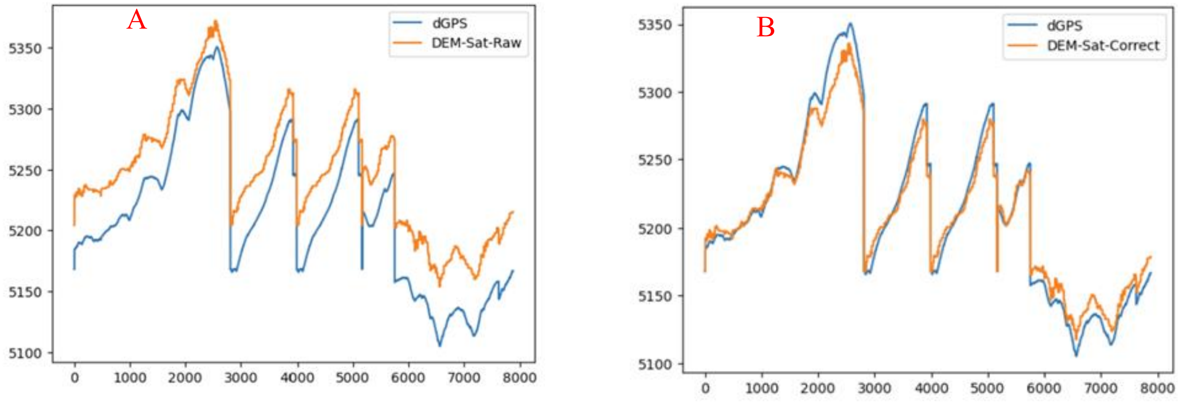

Figure 4: A) Observed Difference in the field-based surface elevation and the Satellite obtained Elevation.B) Corrected DEM, accurately in aligned with the field obtained data)

To delineate the glacier boundary, a recently available free Sentinel-2 image from 2024 with a spatial resolution of 10 meters was used. The glacier terminus was mapped using data collected during the field survey. A 1-meter resolution DEM, acquired a few years ago, was utilized to extract glacier surface area using the glacier boundary polygons. However, the acquired 1 m DEM had some elevation difference with the actual field based dGPS glacier surface elevation (Fig. 4a). Finally, a correction factor was applied to lower down the DEM surface elevation and match with the field-based surface elevation (Fig. 4b) and were used for the calculation of area-averaged glacier mass balance. The extracted hypsometry within the 50 m elevation band for 2022 and 2024 is shown in figure 5.

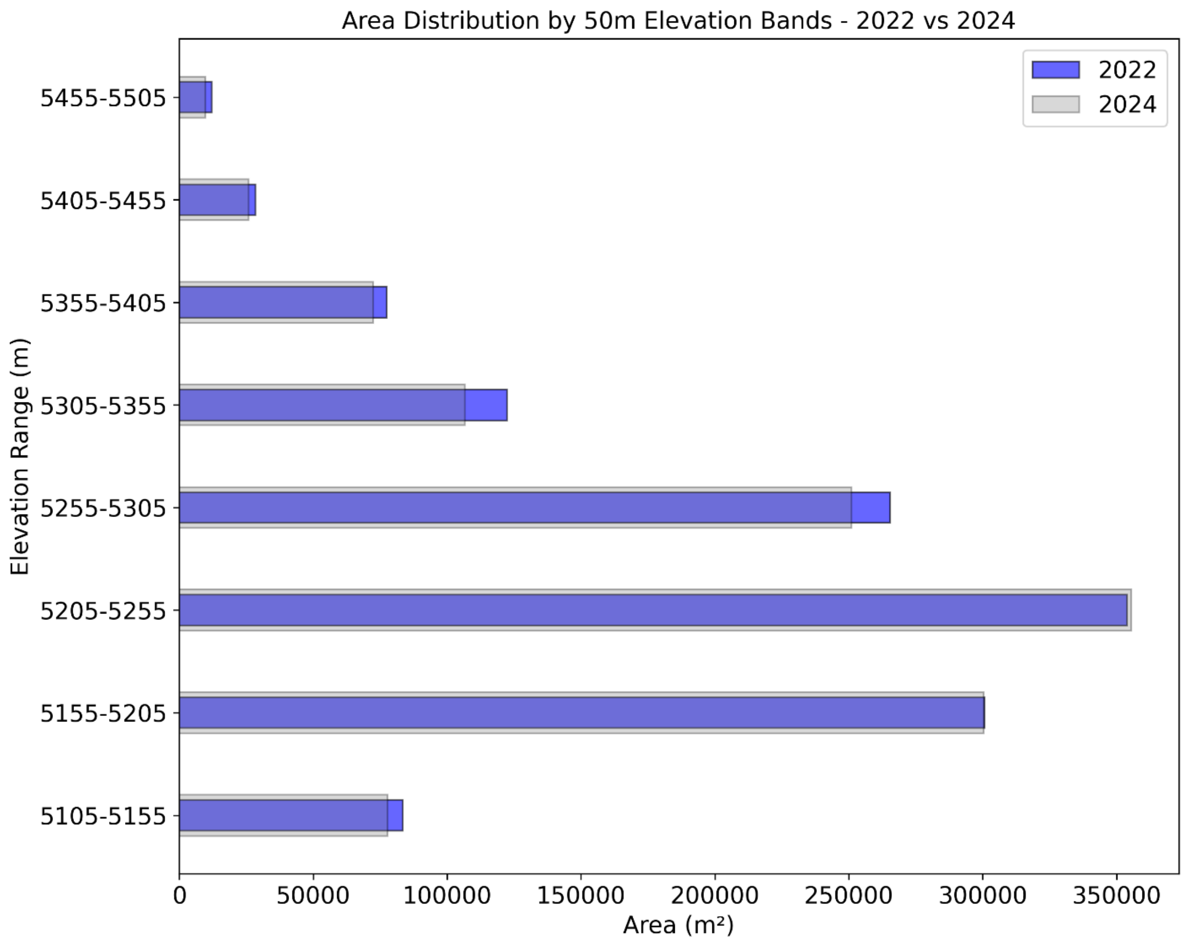

Figure 5: Shodug glacier hypsometry for the year 2022 and 2024

6. Result

Table 1: Shodug glacier Mass Balance

Elevation (m)	Average Elevation difference	Average Area 2023-2024(m^2)	Point Mass Balance mm w.e.a^{-1}	Area Average Mass balance mm w.e.a^{-1}
5105-5155	-5.7556	80696.97	-2582.88	-170.60
5155-5205	-4.73720	300510.62	-2141.97	-526.87
5205-5255	-4.39187	354703.14	-1999.59	-580.55
5255-5305	-3.82914	258238.76	-1761.62	-372.36
5305-5355	-3.24766	114514.45	-1515.37	-142.04
5355-5405	-2.62000	74905.72	-1246.40	-76.42

5405-5455	-2.02000	27223.07	-992.00	-22.10
5455-5505	-1.43000	10906.13	-742.00	-6.623
		Glacier Mass Balance		-1897.597022

The table 1 shows the point mass balance, area-averaged mass balance and a total glacier mass balance. It also shows the average surface elevation difference for the year 2022 and 2024.

From the point mass balance, we can deduce that surface lowering decreases with increasing elevation. This is consistent with the findings of Phuntsho and Fujita (2016), who reported maximum surface lowering at lower elevation and less at higher elevations.

The Shodug Glacier exhibits a negative mass balance, consistent with the trends observed in the two other benchmark glaciers. Between 2022 and 2024, it experienced a mass loss of -1897.60 mm w.e. a^{-1} (Table 1) over a total surface area of 1.2217 km^2. In addition, the glacier terminus retreated by 48.62 m. To account for spatial variability along the terminus front, multiple transect lines were drawn, and the average retreat was computed to determine the final terminus displacement (Fig. 6).

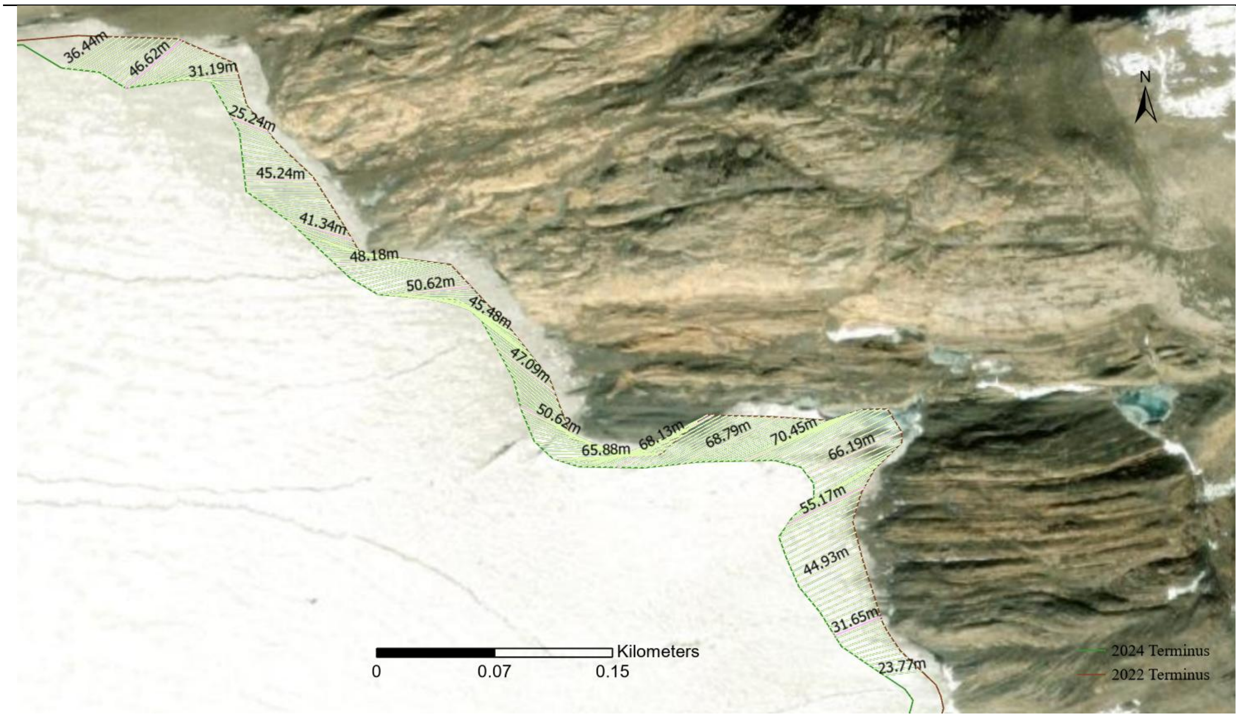

Figure 6: Shodug Terminus recession over the time

Using the available data, terminus retreat was calculated due to its importance in understanding glacier dynamics. Terminus data was collected using differential GPS (dGPS) to precisely track the glacier's terminus position over time. The terminus retreat for Shodug was calculated using the 2022 terminus as the reference point, with zero retreat assigned to that year for calculating the extent of the terminal recession in subsequent years.

7. Uncertainty Estimation in Area-Average Mass Balance

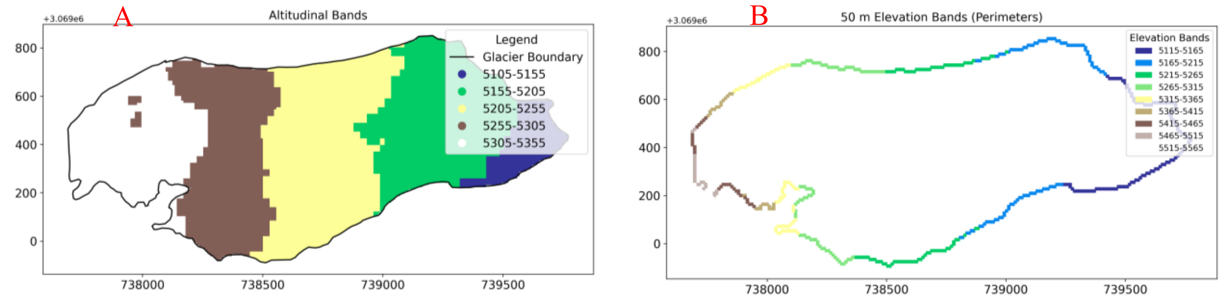

Figure 7: A) Altitudinal band. B) Perimeter over different elevation band

The area-average mass balance estimation is associated with three main uncertainties:

1. Uncertainty in the mass balance at each altitudinal band (db_Z; mm w.e. a⁻¹) is calculated for the bands shown in Fig. 7a.

2. Uncertainty from the glacier boundary delineation (dA_Z; m²), and

3. Uncertainty from the assumed density of ice and snow (db_ρ; mm w.e. a⁻¹).

These uncertainties affect the reliability of the estimated area-average mass balance and are incorporated into the final value as a ± range, indicating possible variation. The combined uncertainty (σ) is calculated following the methodology described in Tshering and Fujita (2016) as:

$$\sigma = \frac{\sum A_Z db_Z + \sum dA_Z |b_Z| + \sum A_Z db_\rho}{A_T}$$

Where:

- A_Z is the area within a 50 m altitudinal band,

-A_T is the total glacier area,

- b_Z is the mass balance at each band, and
- $|b_Z|$ is the absolute mass balance.

The uncertainty from the boundary delineation (dA_Z) is computed as:

dA_Z = 0.5 × pixel resolution × perimeter at each 50 m band

Given the Sentinel-2 MSI image resolution of 10 m, dA_Z is based on half the pixel size (i.e., 5 m) multiplied by the perimeter of the glacier outline at each altitudinal band (Fig.7b).

The uncertainty from the density assumption db_ρ arises from variability in the assumed densities of ice and snow. Following standard assumptions, a density uncertainty of 30 kg m^{-3} for ice and 100 kg m^{-3} for snow is used. These two values are averaged to represent the overall density-related uncertainty in mass balance estimation.

The standard deviation (db_Z) of the mass balance across altitudinal bands, representing the uncertainty from spatial mass balance variation, is calculated as:

$$db_Z = \sqrt{\frac{1}{N}\sum(b_Z - \overline{b_Z})^2}$$

Where N is the number of elevation bands and $\overline{b_Z}$ is the mean mass balance.

The total uncertainty estimated for the area-average mass balance is ±295.11 mm w.e. a^{-1}. This means the annual area-average mass balance for the glacier in 2024 is:

-1897.597022 ± 295.11 mm w.e. a^{-1}

indicating that the actual value may vary by this margin due to the cumulative uncertainties discussed above.

8. Results and Discussion

The glacier change assessment of Shodug Glacier over the 2022–2024 monitoring period highlights clear signs of mass loss and dynamic retreat in response to ongoing climatic stress. Using high-precision RTK GNSS data and Inverse Distance Weighting (IDW) interpolation, surface elevation differences were calculated and applied to generate digital elevation models (DEMs) that allowed for accurate estimation of glacier-wide geodetic mass balance. The annual area-average mass balance for the glacier in 2024 is calculated at –1897.60 ± 295.11 mm w.e. a^{-1}, revealing significant negative mass balance over the period. This loss is most pronounced at lower elevations, where surface melting dominates due to increased exposure to warmer atmospheric conditions. These findings are consistent with the results of Tshering and Fujita (2016), who observed markedly enhanced mass loss at lower elevations of benchmark glaciers in the Bhutan Himalaya, highlighting elevation-dependent sensitivity to climatic warming. Their work also noted that the mass loss was dominated by melt at the glacier tongue, with minimal input from snowfall in lower accumulation zones.

The magnitude of ice loss observed at Shodug Glacier is consistent with other benchmark glaciers in Bhutan, such as Gangju La and Thana, and aligns with regional estimates across the eastern Himalaya. Previous studies (e.g., Brun et al., 2017; Wagnon et al., 2023) have reported annual mass balances ranging between –0.4 and –1.2 m w.e., with clean, debris-free glaciers such as Shodug falling toward the higher end of this range. These results highlight the sensitivity of small, low-lying valley glaciers to even slight shifts in climatic conditions.

To ensure the robustness of these findings, uncertainty analysis was conducted following the established methodology of Tshering and Fujita (2016). This approach integrates cumulative potential errors arising from GNSS measurement precision, glacier boundary delineation, elevation interpolation, and assumed ice density, thereby providing a transparent and consistent quantification of uncertainty. Importantly, the total uncertainty of ±295.11 mm w.e. a^{-1} observed in this study lies well within the range reported by Tshering and Fujita (2016), confirming the comparability and reliability of the results. This consistency strengthens confidence in the reported mass balance estimates and supports their use as a credible benchmark for ongoing and future glacier monitoring efforts in the Bhutan Himalaya.

In addition to surface thinning, the terminus of Shodug Glacier exhibited a horizontal recession of approximately 48.62 m during the assessment period. This observed retreat corresponds with documented terminus shifts in comparable glaciers across Bhutan, such as Thana and Gangju La, which have shown annual retreats in the range of 25 to 60 m. The spatial variability along the terminus front at Shodug—where the central section showed the greatest recession—is likely influenced by variations in local slope, ice thickness, and surface energy balance. Such differential retreat patterns are supported by previous research (Bhambri et al., 2011; Dehecq et al., 2015) that link the geometry and dynamics of the glacier tongue to localized responses to warming.

Overall, the findings from Shodug Glacier provide further evidence of sustained glacier recession in the Bhutan Himalaya, driven by rising temperatures and potential changes in precipitation regimes. The consistency of these results with regional trends emphasizes the urgency of maintaining long-term glacier monitoring initiatives, particularly in light of Bhutan's heavy reliance on cryosphere-fed river systems for hydropower and water resources. As a designated benchmark glacier, Shodug offers critical insights into the behavior of clean glaciers under changing climatic conditions, and its continued observation contributes to the regional understanding promoted by broader frameworks such as the Third Pole Monitoring Programme and the HKH Cryosphere Monitoring Initiative.

9. Conclusion

Shodug Glacier exhibits a negative mass balance trend, consistent with global and regional patterns of glacier retreat driven by a warming climate. The observed surface lowering, particularly at lower elevations, along with terminus retreat, indicates intensified melting. This study emphasizes the importance of high-resolution geodetic methods in assessing glacier health. Continued monitoring is crucial not only for informing national strategies but also for contributing to global awareness, especially in alignment with the recent initiation of World Day for Glaciers.

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