Glacier Mass Balance Studies on Gangju La

2023-2024

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 report presents the 2023–2024 glacier mass balance assessment of Gangju La Glacier, a benchmark glacier located in the headwater of Pho Chu. The study employed an in situ geodetic method using high-precision RTK GNSS equipment (R10-2) to evaluate changes in surface elevation and glacier terminus position. The results indicate a continued negative glacier mass balance trend observed since 2003. For the monitoring year, the glacier experienced a significant mass loss of –2198.359 mm w.e. a^{-1}, one of the highest mass loss ever since 2003 over a surface area of 0.1777 km^2, with a terminus retreat of 38.74 meters measured along the center line of the glacier. Hypsometric analysis showed that surface lowering was observed to be higher at lower elevation, decreasing with elevation. The cumulative glacier mass balance from 2004 to 2024 reveals two distinct linear recession phases, interrupted by a gap in monitoring between 2004 and 2011. These findings are critical insights into the regional impacts of climate change on Bhutan's cryosphere and highlight the importance of sustained glacier monitoring efforts by the National Center for Hydrology and Meteorology (NCHM).

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1.Introduction

Mountain glaciers are critical components of the Earth, acting as natural freshwater reservoirs that sustain ecosystems, agriculture, hydropower, and drinking water supplies. Their seasonal meltwater is especially important during dry periods, providing a steady flow to both upstream and downstream communities. However, these frozen land masses are increasingly under threat due to the accelerating impacts of climate change, making glaciers one of the most visible and measurable indicators of global warming.

In response to this crisis, the global scientific community officially established World Day for Glacier on March 21st, 2025. The initiative aims to raise awareness of the rapid glacier retreat occurring worldwide and its consequences for water security, sea-level rise, and climate systems. The observance emphasizes the urgency of sustained glacier monitoring and coordinated climate action, as glaciers continue to lose mass at unprecedented rates.

Scientific observations have consistently confirmed the scale and acceleration of glacier mass loss over recent decades. Glaciers have been retreating since the early 20th century across most regions (IPCC, 2023), with significantly increased rates in the 21st century (Zemp et al., 2019). Hugonnet et al., 2021) reported that nearly all mountain glaciers globally are now out of balance under the current climate, losing an average of 267 ± 16 gigatonnes (Gt) of ice annually between 2000 and 2019. Supporting these findings, the UNESCO (2025) report estimates that over 9,000 Gt of ice have been lost since 1975, an amount equivalent to an ice block the size of Germany and 25 meters thick. Similarly, data from the World Glacier Monitoring Service (WGMS) reveal 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 freshwater use over a 30-year period.

Even future scenarios show the cause of concern. The World Meteorological Organization (WMO) warns that, without rapid reductions in greenhouse gas emissions, 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 the 21st century. This projected loss would have severe implications for regional water availability, disaster risk, and ecosystem stability.

The glaciers in the Himalayan region, including Bhutan, are showing similar global trends. Located within the broader Hindu Kush Himalaya (HKH), a region that is warming faster than the global average. Bhutan's glaciers are experiencing significant retreat. According to the Bhutan Glacier Inventory 2018, there are 700 glaciers spanning an area of 629.55 km², which accounts for approximately 1.64% of Bhutan's total land cover. However, these glaciers revealed alarming rates of shrinkage and thinning. Current estimates suggest Bhutan's glaciers are losing mass, with widespread evidence of negative glacier mass balance and terminal retreat for all the benchmark glaciers.

These observations are based on the observed and estimated data from the annual glacier monitoring program on three bench marked glaciers in Bhutan. The country's first formal glacier documentation was undertaken through the Inventory of Glaciers and Glacial Lakes (Mool et al., 2001), published by ICIMOD. Since then, Bhutan has expanded its glacier monitoring activities through a combination of remote sensing and field-based observations. As part of its cryosphere monitoring strategy, NCHM has benchmarked three glaciers, Gangju La, Thana, and Shodug, for annual monitoring of mass balance assessments and long-term monitoring.

Among these, Gangju La Glacier, located in the headwaters of the Pho Chhu in northern frontier of Bhutan is a small clean type glacier. Monitoring of this glacier began in 2003 and its strategic location, typical morphological condition, and accessibility make it an ideal reference site for studying glacier-climate interactions in the area. This technical report focuses on the assessment of Gangju La glacier for mass balance using glacier surface elevation datasets and glacier outlines from 2023 and 2024.

2.Aim and Objective

The primary aim of this study is to assess recent changes in the mass balance and terminus position of Gangju La Glacier through in-situ based geodetic method, thereby contributing to Bhutan's long-term glacier monitoring and climate adaptation efforts.

3.Study Area

3.1 Location

A clean type Gangju La Glacier is located in WGS 84/UTM zone 45N of Bhutan at 27.94°N, 89.95°E (Figure 1) with an approximate area of 0.3 km² (NCHM Annual report, 2023). It extends from an elevation of 4900 to 5200 m.a.s.l., referred to as "PPhgr16_189" in an inventory compiled by the National Center for Hydrology and Meteorology (NCHM, 2018).

3.2 Accessibility

This route can be accessed via two options. The first route is via Gasa-Laya-Tarina-Gangju La, which takes seven days on foot. The other route is via Ramina-Gangju La and takes five days to reach the study site. It is en route to Lunana Gewog of Gasa Dzongkhag.

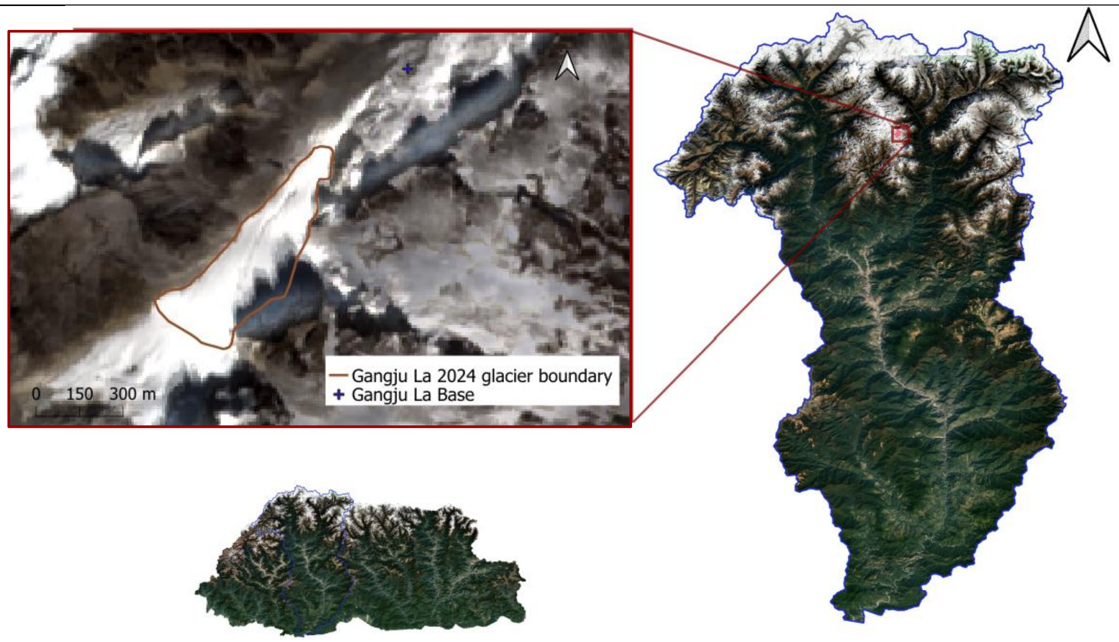

Figure 1: Location of Gangju La Glacier at the headwaters of Pho Chu within the Punatshangchu basin (outlined in blue). The background is a Sentinel-2 True Color Composite.

4. Data and Methodology

4.1 Data Acquisition

Gangju La Glacier is located en route to Lunana Gewog of Gasa Dzongkhag. It is challenging to collect data using direct methods because of human disturbances. Therefore, the monitoring team relies on only in-*situ* geodetic methods to continuously monitor this glacier.

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 (reference point), 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 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.

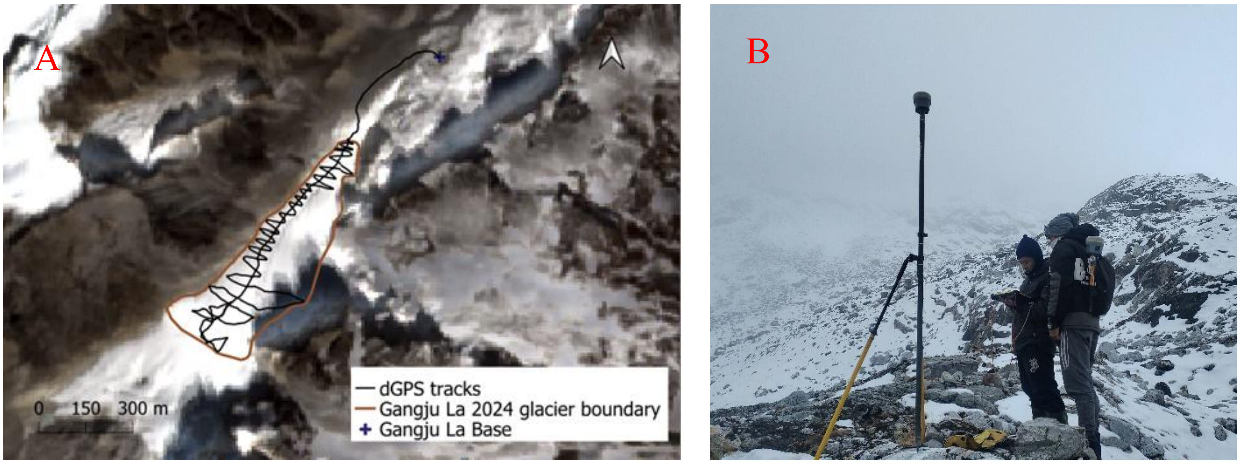

Figure 2: A) dGPS survey tracks. B) Base set up. The background is a Sentinel-2 True Color Composite.

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 2023-2024. 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), the average of the area within the 50 m altitude band of two different survey years is considered.

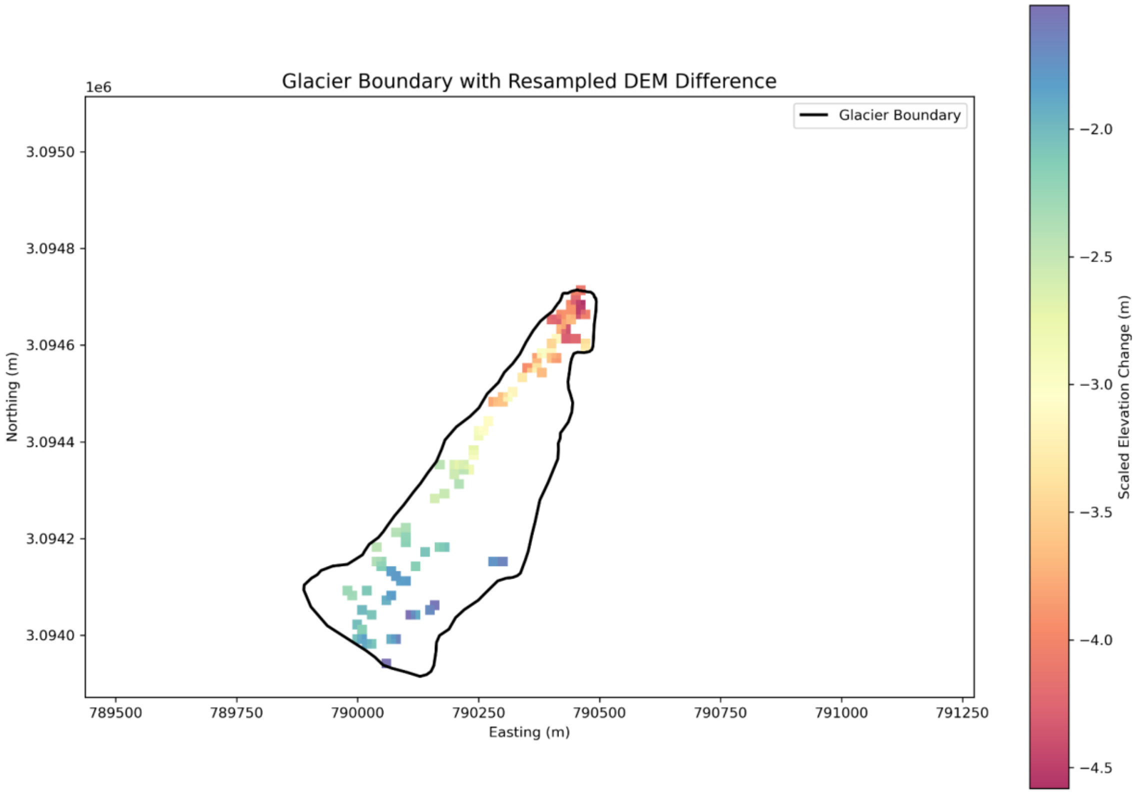

Figure 3:DEM difference calculated for the years 2023–2024. The raster values were resampled using a factor of 10 to enhance visual clarity.

5. Hypsometry

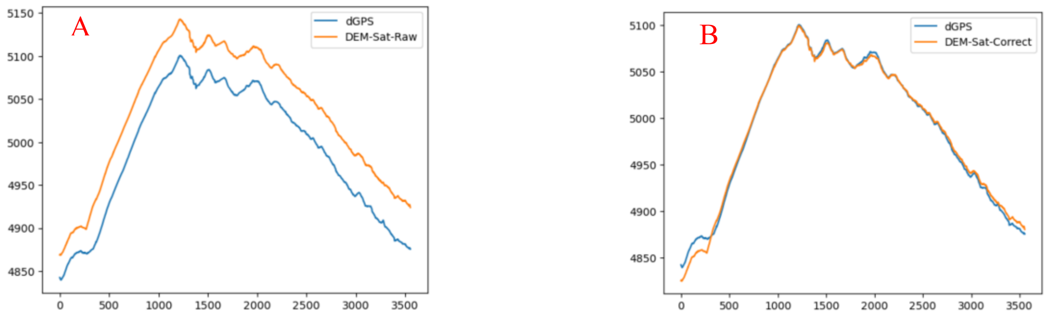

Figure 4: A) Observed Difference in the field-based surface elevation and the Satellite obtained Elevation.B) Corrected DEM, accurately in aligned with the field obtained data)

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 2023 and 2024 is shown in figure 5.

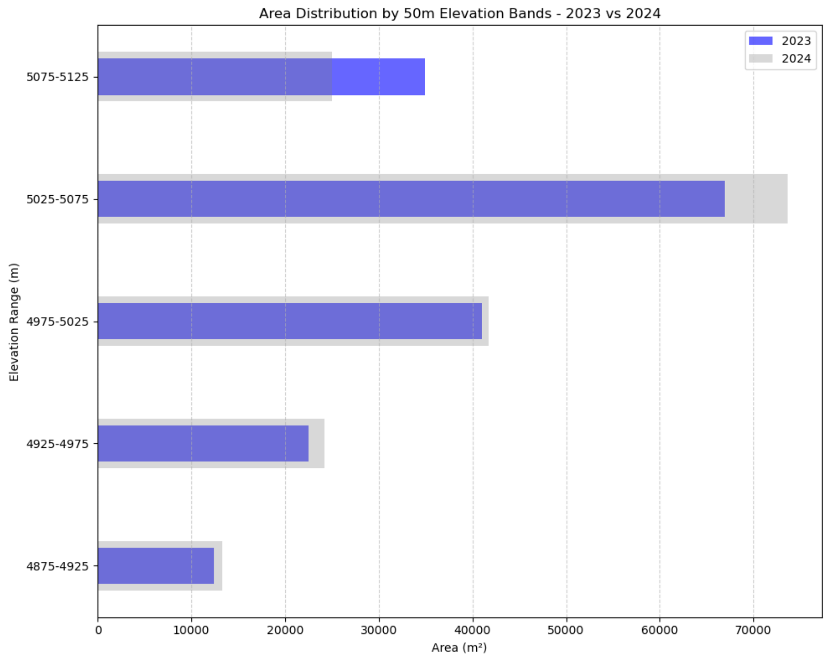

Figure 5: Gangju La glacier hypsometry for the year 2023 and 2024

6. Result

Table 1: Ganju La 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}
4875-4925	-3.8952	12821	-3426.17	-247.09
4925-4975	-3.5349	23397	-3097.14	-407.62
4975-5025	-2.7610	41358.5	-2399.80	-558.31
5025-5075	-2.1804	70260.5	-1780.53	-703.72
5075-5125	-1.8720	29934.5	-1672.34	-281.60
		Glacier Mass Balance		-2198.359

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 2023 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 Gangju La glacier has been exhibiting negative mass balance since 2003. For the year 2023 to 2024, it recorded comparatively higher mass loss with Glacier Mass Balance of -2198.359 mm w.e.a^{-1}(Table 1), over total glacier surface area of 0.1777km^2. Additionally, the terminus retreated by 38.74m measured along the center line of the glacier flow line (Fig. 6).

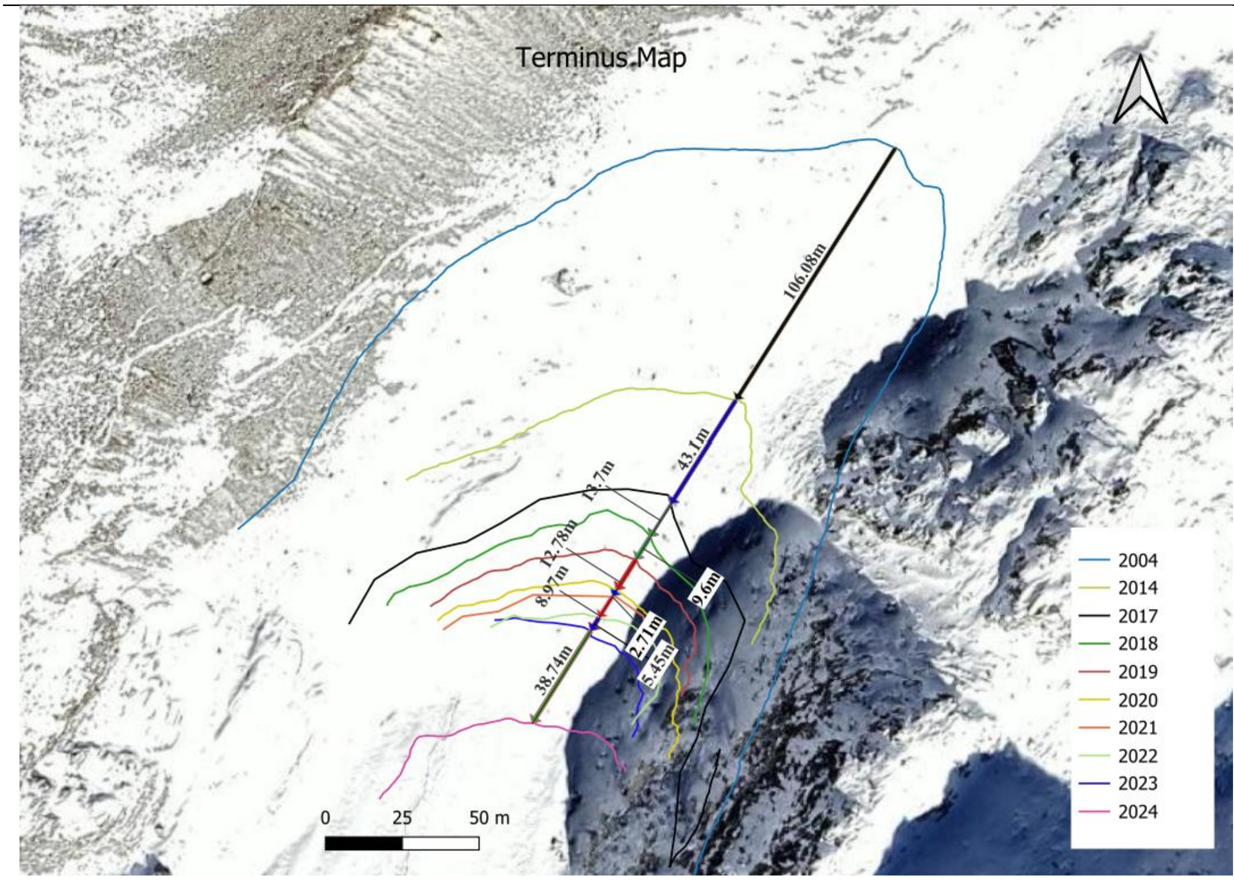

Figure 6: Gangju La Terminus recession over the time

7.Cumulative Glacier Mass Balance and Terminus Recession

The cumulative glacier mass balance of Gangju La appears to show a linear retreat during the periods 2004–2011 and 2014–2017(Fig.7), which is attributed to the lack of data collection during these intervals. No studies were conducted between 2004 and 2011. A single observation was made in 2014 after a seven-year gap, and the National Center for Hydrology and Meteorology has been conducting annual studies from 2018 to the present. The cumulative glacier mass balance up to 2024 is -35262.58 mm w.e. a^{-1} (Table 2).

Table 2:Cumulative Glacier Mass Balance (displayed few rows of the table)

Sl.No	Year	AGMB	CGMB
1	2004	-1230	-1230
2	2005	-1790	-3020
18	2022	-1764.677	-31325.416
19	2023	-1738.805	-33064.22108
20	2024	-2198.35	-35262.58

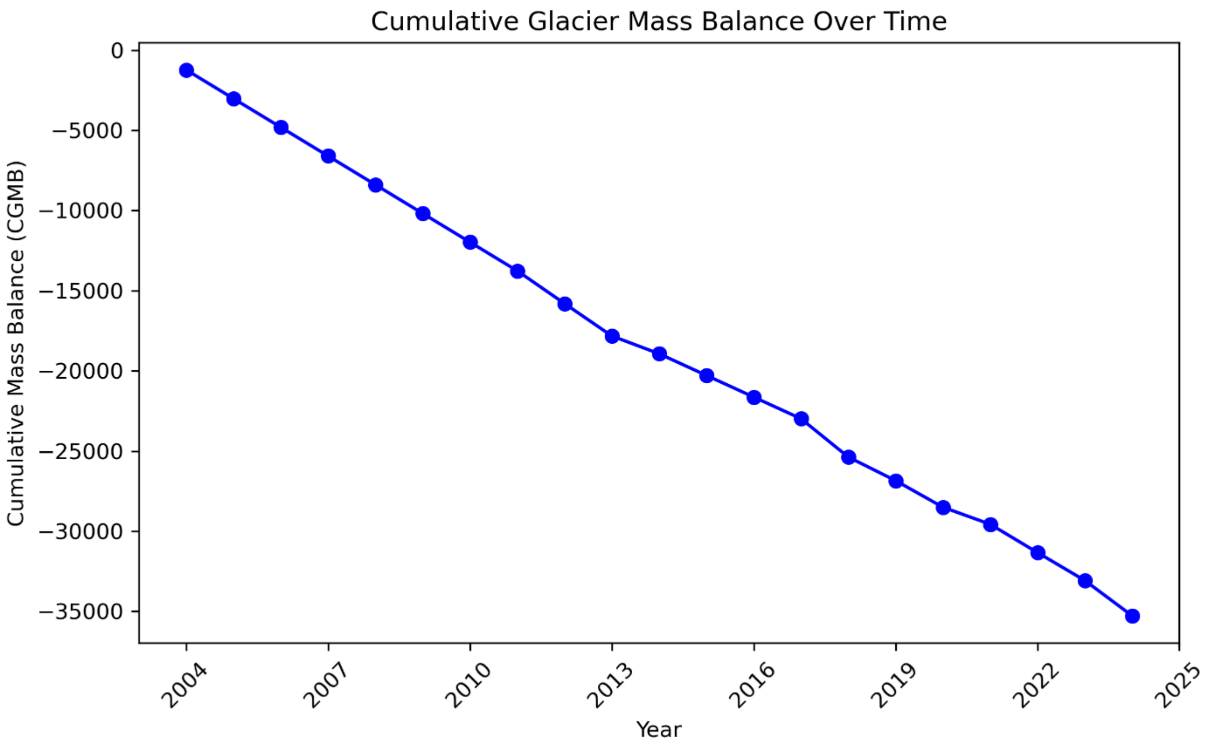

Figure 7:Cumulative Glacier Mass Balance over time

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 Gangju La was calculated using the 2004 terminus as the reference point, with zero retreat assigned to that year for calculating the extent of terminus recession in subsequent years. The terminus retreat from 2023 to 2024 was observed to be greater compared to any other two consecutive years. Since 2004, the glacier terminus has retreated by approximately 202.39 meters (Table 3). The glacier terminus is retreating over time, and the trend of this retreat is shown in Fig. 8. There is no record of terminus data from 2005 to 2013 and from 2015 to 2016, so the line shows a linear terminus retreat during these periods (Fig.8).

Table 3:Cumulative Terminus Recession Over Time

Sl.No	Year	Terminus Retreat(m)	Cumulative Terminus Retreat(m)
1	2004	0	0
2	2014	106.08	106.08
3	2017	43.1	149.18
4	2018	13.7	162.88
5	2019	9.6	172.48
6	2020	12.78	185.26
7	2021	2.71	187.97
8	2022	8.97	196.94
9	2023	5.45	202.39
10	2024	38.74	241.13

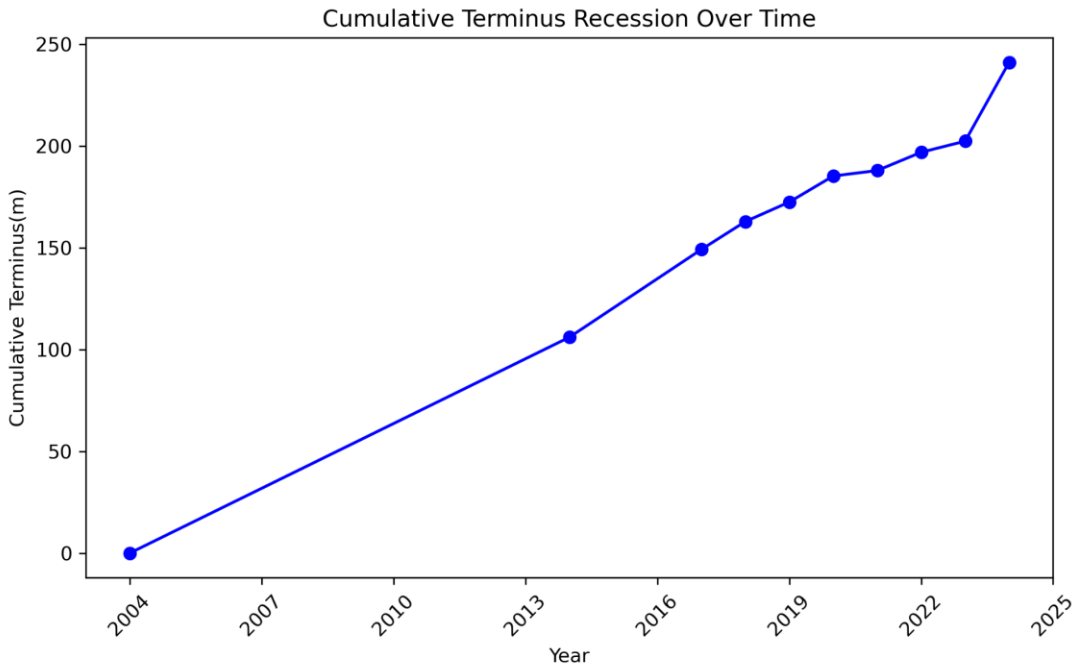

Figure 8:Cumulative Terminus Recession Over Time

8. Uncertainty Estimation in Area-Average Mass Balance

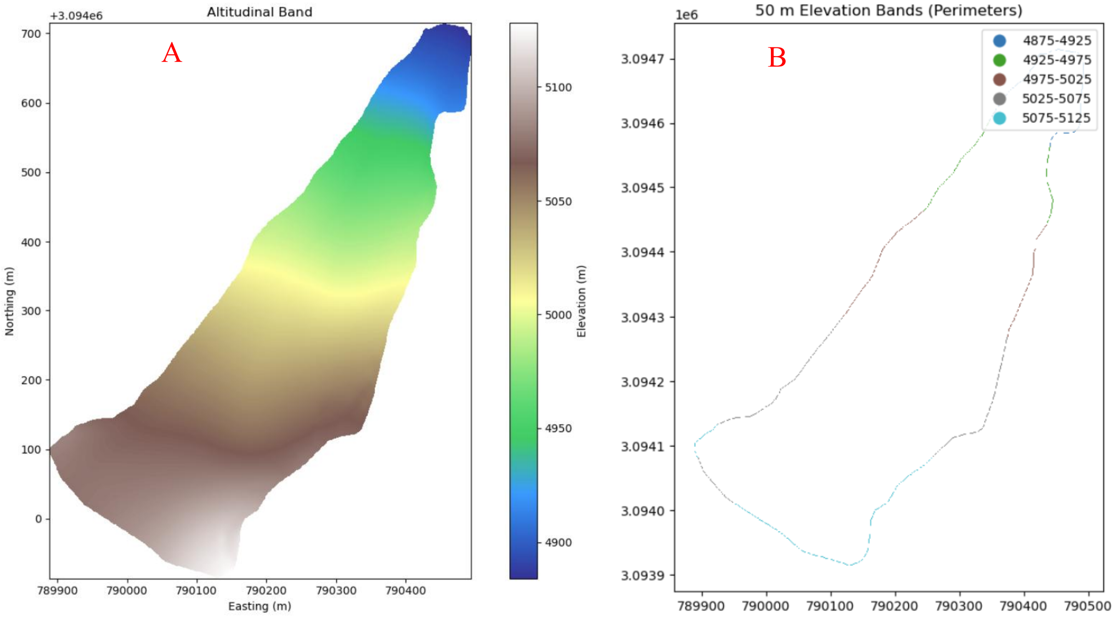

Figure 9: A) Altitudinal band. B) Perimeter over different elevation band

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. 9a.

2. Uncertainty from the glacier boundary delineation (dA_Z; m^2), 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.9b).

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 ±272.074 mm w.e. a^{-1}. This means the annual area-average mass balance for the glacier in 2024 is:

-2198.359 ± 265.74 mm w.e. a^{-1}

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

9. Conclusion

Gangju La Glacier continues to exhibit a negative mass balance trend, consistent with global and regional patterns of glacier retreat driven by a warming climate. The 2023–2024 assessment recorded one of the highest annual mass losses since monitoring began, highlighting the glacier's increasing vulnerability. 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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