Impact of Climate Change on Glacier Mass Balance: Geodetic Mass Balance Study on Kimshung Glacier from 2015 To 2025

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Abstract

Millions of people depend on glaciers for drinking water, irrigation, and hydropower generation. Being sensitive to warming climate, Himalayan Glaciers lag long term mass balance data. In this study we measure the geodetic mass balance and surface change of Kimshung Glacier, a clean glacier in the central Nepal from the period 2015 to 2025. The method combines DEM differencing of an ASTER DEM from 2015 against a sentinel-1 derived DEM from 2025. The DEM differencing was done after co-registration following Nuth and Kaab (2011). The surface velocity from the ITS_LIVE (from 1990 to 2018) archive and ERA5 (from 1979 to 2024) reanalysis of temperature and precipitation data added the objectives of the study to better understand present glacier scenario. On average, the glacier surface lowered by 8m to 10m, and thinning was strong between 5200m to 5800m. The mean mass balance is found to be −0.64 m w.e. yr^{-1} with cumulative loss of -6.4 m w. e. over the decade. Glacier area shrank by 1.7% from 3.428 to 3.369 Km^2. Peak surface velocity rise from about 5 to 7 m yr^{-1} in 1990 to about 30 to 32 m yr^{-1} by 2018. Overall, the results show a steady loss of mass driven by temperature. Saying that, the total estimate has quite a big uncertainty of ±6.3 m w.e. To reduce that uncertainty in future studies, we'll need to use DEMs from the same sensor and combine them with actual field data.

Keywords: DEM differencing; geodetic mass balance; Kimshung Glacier; Langtang Valley; Nepal Himalaya

Introduction

Glaciers in the Hindu Kush Himalaya (HKH) hold the largest store of ice outside the polar regions and respond directly to changes in air temperature and precipitation, which makes them reliable indicators of a warming climate (Bolch et al., 2012; Hock et al., 2019). They also sustain river flow, agriculture, hydropower, and ecosystems for hundreds of millions of people downstream (Immerzeel et al., 2010, 2020). Across Nepal, the warming rate of 0.02 to 0.16 °C yr^{-1} exceeds the global mean over land, and glaciers have responded with negative mass balances of about −0.3 to −0.8 m w.e. yr^{-1}, shrinking area, and an upward shift of the equilibrium line altitude (Shrestha et al., 1999; Khadka et al., 2023a).

These changes are well documented at the national scale. Glaciers in Nepal lost about 24 % of their area between roughly 1980 and 2010 (Bajracharya et al., 2014), while the surface area of glacial lakes expanded by about 25 % (0.83 % yr^{-1}) between 1987 and 2017, raising the risk of glacial lake outburst floods (Khadka et al., 2018; Khadka et al., 2023a). Most field and remote sensing studies, however, concentrate on eastern and central Nepal, especially the Everest region, while the western and several central glaciers remain understudied (Khadka et al., 2023b).

The Langtang Valley in central Nepal is a key research site that contains both debris-covered and clean-ice glaciers. Earlier work in the valley has reported widespread thinning between 1974 and 2015, with rates accelerating from −0.24 ± 0.08 m yr^{-1} over 1974 to 2006 to −0.45 ± 0.18 m yr^{-1} over 2006 to 2015 (Pellicciotti et al., 2015; Ragettli et al., 2016). Updated geodetic assessments after 2015 are scarce, which leaves a gap in our understanding of how Langtang glaciers have responded to recent warming, shifts in precipitation, and disturbances such as the 2015 Gorkha earthquake. Glacier response in this region is also far from uniform, because debris cover, slope, aspect, and elevation each affect melt in different ways. For that reason, glacier-specific studies are still needed (Fujita & Sakai, 2014).

Remote sensing and geodetic methods get around the logistical difficulty of in-situ measurements in this remote terrain, and they make it possible to map elevation and volume change over time (Nuimura et al., 2012; Berthier et al., 2007). DEM differencing in particular gives a spatially distributed estimate of surface elevation change, and after a density conversion, of mass balance. Kimshung Glacier, a clean-ice glacier in the Langtang Valley, has not yet been assessed with this approach over the most recent decade.

This study sets out to fill that gap. We quantify the geodetic mass balance and surface changes of Kimshung Glacier from 2015 to 2025. The specific objectives are: (1) to measure the change in glacier area; (2) to estimate surface elevation change and mass balance through DEM differencing; and (3) to interpret the spatial pattern of change in relation to slope, aspect, surface velocity, and local climate trends.

Materials and Methods

Study Area

The Langtang River basin lies in the monsoon-dominated central Himalaya, just north of Kathmandu, Nepal. It drains 585 km² of land, of which about 155 km² is glacierized. Elevations range from 1406 m at Syafru Besi up to 7234 m at the summit of Langtang Lirung (Pellicciotti et al., 2017). The Indian summer monsoon, running roughly from June to October, delivers more than 70 % of the annual precipitation. November through May is comparatively dry (Fugger et al., 2022). Most of the glaciers in the valley are debris-covered, but Kimshung is one of the few clean-ice glaciers. We confirmed this through the Normalized Difference Snow Index (NDSI) and field observation. During field inspection we also noticed that the glacier terminus has begun to gather some debris, most likely from bedrock erosion and aeolian input (Figure 1).

Figure 1

NDSI of Langtang National Park using Sentinal-2 Image with major glaciers.

Data

We used a combination of multi-source DEMs and optical imagery (Table 1). Glacier boundaries were drawn from cloud-free Sentinel-2 imagery using the NDSI, and we corrected the boundaries manually on false-colour composites where needed. For surface elevation change, we differenced the ASTER DEM from 2015 against a DEM generated from Sentinel-1 data acquired in 2025, processed in SNAP software. The SRTM DEM from around 2000 served as a reference for co-registration over stable terrain. Surface velocity came from the NASA MEaSUREs ITS_LIVE archive (Gardner et al., 2018). Air temperature and precipitation trends from 1979 to 2024 were drawn from the ERA5 reanalysis. Processing and mapping were done mostly in QGIS and Python.

Table 1

Datasets, acquisition dates, resolutions, and purpose.

Dataset	Date	Resolution	Purpose	Source
SRTM DEM v003	2000	30 m	Reference DEM for co-registration	USGS Earth Explorer
ASTER (AST14DMO)	2015	30 m	Baseline DEM for differencing	NASA Earthdata
Sentinel-1	2025	10 m	Source for 2025 DEM (SNAP)	Copernicus
Sentinel-2	2015–2025	10–20 m	Glacier boundary delineation	Copernicus
ITS_LIVE	1990–2018	—	Surface velocity	NASA MEaSUREs
ERA5	1979–2024	—	Temperature, precipitation trends	ECMWF

DEM Differencing and Mass Balance

When DEMs come from different sensors and acquisition dates, both horizontal and vertical offsets need to be corrected before differencing. To handle this, we co-registered the DEMs over stable, non-glacierized terrain using the method of Nuth and Kääb (2011). The method relates the elevation difference to terrain slope and aspect (Equation 1):

$$dh = a \cdot \cos(b - \psi) \cdot \tan(\alpha) + \overline{dh} \quad (1)$$

Here dh is the elevation difference, α is terrain slope, ψ is terrain aspect, a is the magnitude of the horizontal shift, b is its direction, and $\overline{dh}$ is the mean elevation bias. We solved the parameters by least squares. Because both DEMs already share a 30 m resolution, the horizontal shifts were small, and the residual elevation bias was corrected using Equation 1. The mean elevation change of the glacier between 2015 and 2025 was then extracted with zonal statistics, and mass balance was calculated with Equation 2:

$$B = (\Delta V \cdot \rho ice) / (S \cdot \rho water) \quad (2)$$

Here B is mass balance in metres water equivalent (m w.e.), ΔV is the volume change derived from elevation change, S is the mean glacier area, and ρice ($\approx$850 kg m^{-3}) and ρwater ($\approx$997 kg m^{-3}) are the densities of ice and water. We held the glacier boundaries constant over the decade. This choice is consistent with earlier work showing that area change is minimal over periods shorter than 20 years (Bhattacharjee et al., 2023).

Glacier volume and mass change were calculated using xDEM, an open-source Python package (Dehecq et al., 2022). The inputs were the DEM difference (representing surface elevation change), the glacier outline, and the reference DEM. The glacier surface was partitioned into 25 m elevation bins from its minimum to maximum elevation, and the mean elevation change within each bin was extracted from the DEM difference using the glacier outline. Volume change was then computed by multiplying the mean elevation change in each bin by the bin area and summing across all bins. This volume was converted to mass by applying an ice density of 850 kg/m³. Specific mass balance, in meters water equivalent (m w.e.), was obtained by dividing the mass change by the mean glacier area between the two outlines.

Results and Discussion

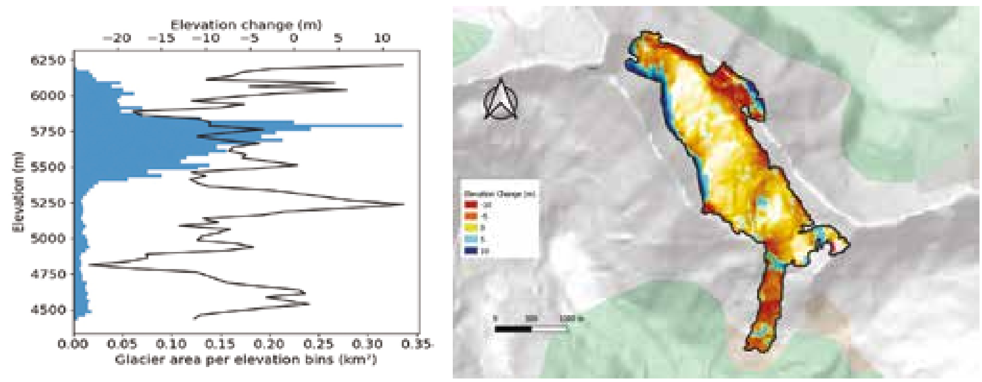
Glacier Area Change

Kimshung Glacier shrank from 3.428 km² in 2015 to 3.369 km² in 2025, a loss of 1.7 % over the decade, or about −0.17% yr^{-1}. The retreat is concentrated at the terminus, where a proglacial setting is developing. The rate is modest but is consistent with the slow, steady retreat seen across the central Himalaya. It also matches the −0.35 % yr^{-1} reported for the Kawari basin in western Nepal and the −0.5% yr^{-1} reported for eastern Nepal (Ojha et al., 2016; Khadka et al., 2023b).

Surface Elevation Change and Mass Balance

Figure 2

Hypsometry of Kimshung Glacier and mean surface elevation change per elevation band, 2015 to 2025.



Note: Hypsometry of Kimshung Glacier (above), Surface elevation change (below).

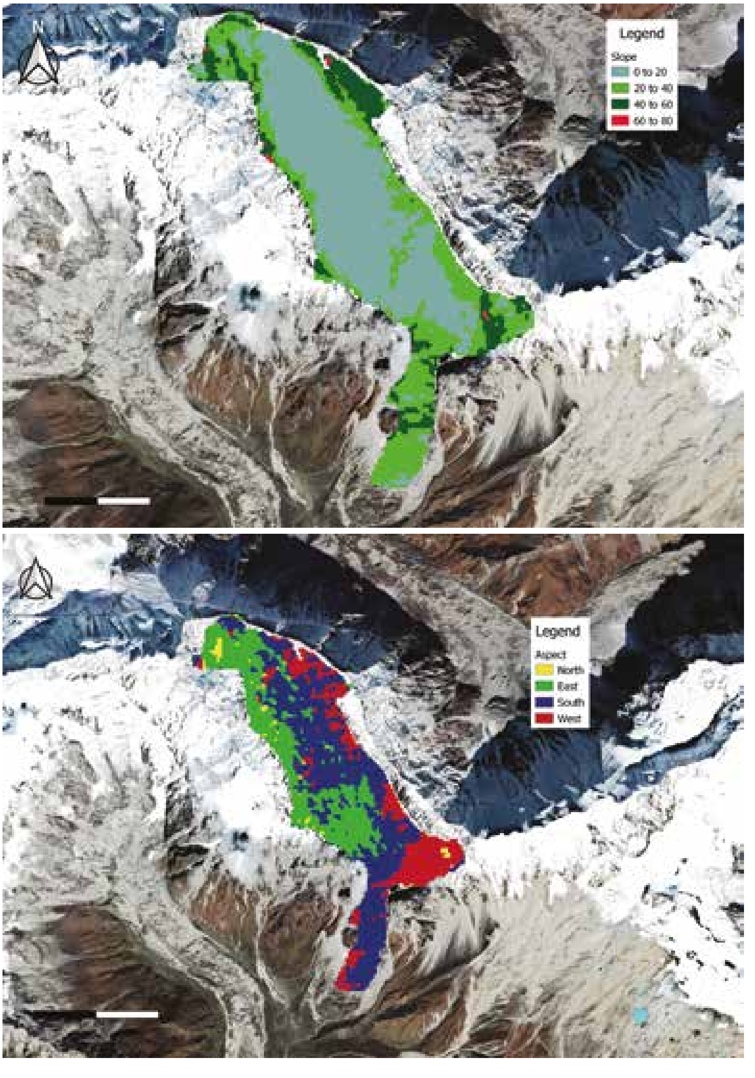
The hypsometric analysis shows that most of the glacier area sits between about 5500 and 5900 m, which is also the core ablation and accumulation zone. Differencing reveals net thinning across nearly every elevation band. The strongest surface lowering, ranging from −5 to −15 m, falls between 5200 and 5800 m, where the area is most concentrated. Across the glacier as a whole, the mean lowering is 8 to 10 m. Some thickening shows up above 6100 m, which we attribute to localized snow accumulation, but the area involved is small and does not offset the wider loss.

The corresponding mass balance is −0.64 m w.e. yr^{-1}, or a cumulative −6.4 m w.e. over the decade. This rate sits within the regional range and is close to that of nearby glaciers. Yala Glacier, for example, lost −0.71 m w.e. yr^{-1} between 2011 and 2017, with a separate estimate giving −0.8 m w.e. yr^{-1}. Debris-covered Langtang glaciers lost −0.37 to −0.45 m yr^{-1}, and Everest glaciers lost −0.26 to −0.32 m w.e. yr^{-1} (Gardelle et al., 2013; Pellicciotti et al., 2015; Ragettli et al., 2016; Acharya and Kayastha, 2018; Khadka et al., 2023a). The agreement of our per-year rate with these independent estimates gives confidence in both the direction and the approximate size of the loss.

Topographic Controls: Slope and Aspect

Figure 3

Slope and aspect of Kimshung Glacier and their relationship with elevation change.



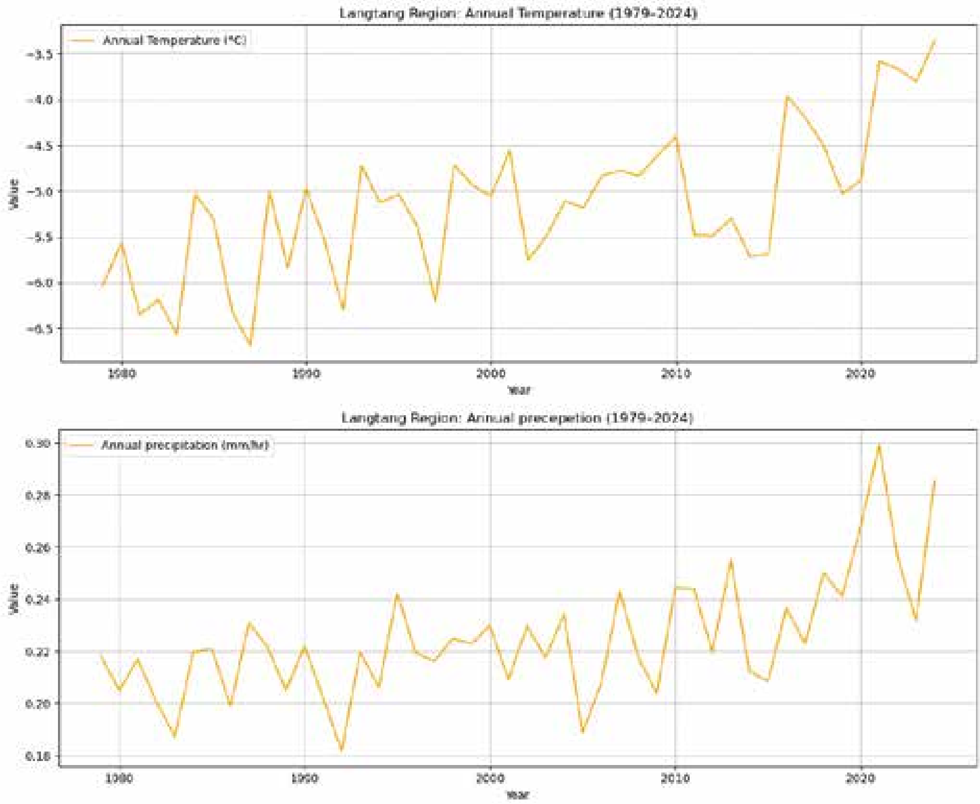
Note: Slope of Kimshung Glacier (above), Aspect of Kimshung Glacier(below)

Slope and aspect shape the spatial pattern of thinning. Steep slopes of 40° to 60° in the ablation zone lost the most surface elevation, which fits with stronger melt and gravitational flow on inclined surfaces. Gentler slopes of 0° to 20° at higher elevations changed very little. South-facing and west-facing slopes thinned the most, probably because they receive more direct solar radiation and develop warmer microclimates. North-facing slopes, by contrast, stayed stable or even gained a little mass, most likely because of shading. Taken together, slope and aspect help explain why the lower, more exposed parts of the glacier are losing mass fastest.

Temperature and Precipitation Trends

Figure 4

Annual mean temperature and precipitation near Kimshung Glacier from ERA5, 1979 to 2024.



Note: Kimshung Glacier average annual temperature (above), Kimshung Glacier average annual precipitation (below).

Figure 4 illustrates the Kimshung glacier yearly average temperature, which clearly demonstrates a warming trend throughout the 45-year period from 1979 to 2024. The average temperature was roughly -5.8°C in 1979 and grows to -3.5°C by 2024, a total increase of roughly 2.3°C. Since 2015, the warming trend has been more noticeable, with the last ten years showing a higher ascent. Significant peaks were recorded in 1981–1982, when the temperature was roughly -5.0°C, and in 2022–2023, when it was roughly -3.8°C. Despite interannual variability, with fluctuations around the trend line, the long-term trajectory is consistently upward, indicating significant regional warming.

The precipitation records from Kimshung Glacier (1979–2024) shows a clear increasing trend, especially after 2015, with peaks in the early 2020s. However, this differs from ERA5-based studies in the Nepal Himalaya, which generally show declining or stable precipitation after bias correction. For example, (Bajracharya et al., 2024) found decreasing precipitation trends in the Narayani Basin, while (Banerjee et al., 2025) linked reduced snowfall and rainfall to glacier thinning in central Nepal. The difference likely comes from the fact that the Kimshung dataset is not bias-corrected, which can overestimate precipitation compared to corrected ERA5 data.

Figure 5

Surface velocity of Kimshung Glacier in 1990, 2000, 2010, 2015, and 2018 (ITS_LIVE).

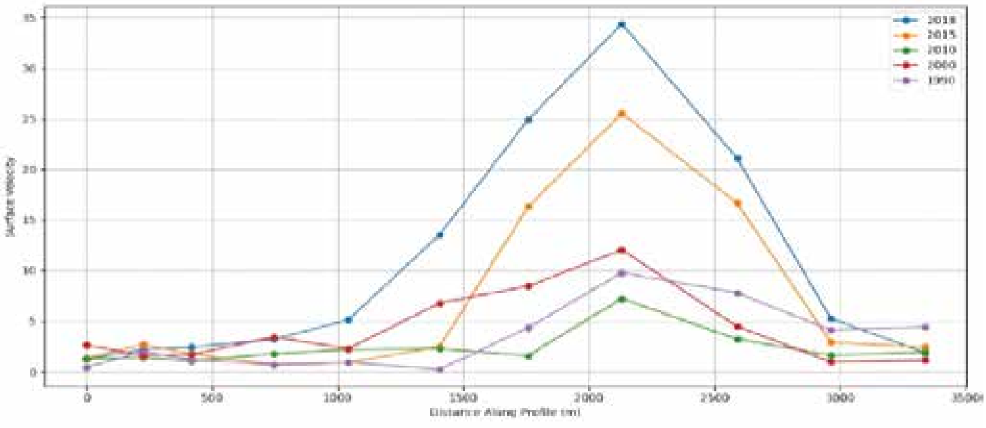


Figure 5 provides an insight into changes in surface flow velocity over the period through a re-analysis of velocity data provided by the NASA measures ITS_LIVE project (Gardner, et al., 2018) and generated using auto-RIFT. Looking at the velocity graph, we see the surface velocity of the Kimshung Glacier measured in meters per year along a distance profile spanning from 0 to 3500 meters from the top part of the glacier. The graph includes data points for five different years: 1990, 2000, 2010, 2015, and 2018, each represented by distinct colors.

Starting with 1990 (purple line), the velocity begins at a low value near zero and gradually increases, peaking around 1000 meters with a velocity of about 5-7 meters per year. After this peak, the velocity decreases steadily towards the end of the profile. In 2000 (red line), the pattern is similar, but the peak velocity is slightly higher, reaching around 8-10 meters per year at the same 1000-meter mark, suggesting a slight acceleration compared to 1990.

By 2010 (green line), the velocity trend shows a more pronounced increase, with the peak shifting slightly to around 1500 meters and reaching approximately 15 meters per year. This indicates a significant speedup over the earlier decades. In 2015 (orange line), the peak velocity climbs further to about 20-22 meters per year, still around the 1500-meter mark, showing continued acceleration. The most striking change occurs in 2018 (blue line), where the velocity peaks at around 30-32 meters per year, again near 1500 meters, before declining sharply towards the end of the profile.

Overall, the trend from 1990 to 2018 shows a clear increase in surface velocity, with the glacier moving faster over time. The peak velocity has not only increased in magnitude but also shifted slightly downstream, suggesting that the glacier's flow dynamics are changing, possibly due to internal deformation or changes in basal sliding conditions.

Uncertainty and Its Implications

- The regional heterogeneity of thinning, varying density assumptions, and possible DEM errors are probably the causes of the significant uncertainty (±6.3 m w.e.) in the mass balance. This has an impact on our ability to measure the overall amount of ice loss.
- However, the general conclusion that the glacier is retreating is strengthened by the constancy of thinning trends across DEM differencing, slope/aspect patterns, and climatic observations.
- The view that increased melting is influencing glacier dynamics is supported by velocity data, even if they are from previous years (up to 2018).

Limitations of the Study

- Methodological Limitation: The study compared ASTER DEM (2015) with DEM created from SNAP for 2025. Since these DEMs were generated using different sensor systems, discrepancies may arise due to differences in resolution, data acquisition methods, and processing algorithms, which could affect the comparability of elevation values.
- Climatic Data Limitation: ERA_5 reanalysis data was used without bias-correction from local station observations. This may have led to an overestimation of the trends in both temperature and precipitation, potentially influencing the accuracy of glacier mass balance projections.

Conclusions

Kimshung Glacier lost mass and thinned between 2015 and 2025. DEM differencing gives a mean surface lowering of 8 to 10 m, a mass balance of −0.64 m w.e. yr^{-1} (cumulative −6.4 m w.e.), and a 1.7 % reduction in area. Thinning is strongest between 5200 and 5800 m, where most of the glacier area lies, and the minor thickening above 6100 m does not offset the loss. Warming of about 2.3 °C since 1979, which accelerated after 2015, is the dominant driver, while the rising surface velocity points to changing flow dynamics. Our per-year mass balance matches regional estimates, but the large cumulative uncertainty means that the magnitude will need to be confirmed with consistent-sensor DEMs and field measurements. Sustained monitoring of clean-ice glaciers such as Kimshung is essential for projecting future water availability in glacier-fed Himalayan basins.

Recommendations for Future Work

- Use DEMs from a consistent sensor, or apply inter-sensor calibration, to reduce elevation-change uncertainty.
- Bias-correct ERA5 (or other reanalysis) against local station data before interpreting climate trends.

- Combine remote sensing with field-based mass balance measurements to validate the geodetic results.
- Extend the velocity record beyond 2018 to cover the full study period.

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