Cryosphere change in the warming Himalaya: Snow cover and snowline trends in Nepal's Langtang Basin (1988-2024)

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Abstract

Snow-Covered Area (SCA) and its migrating lower boundary, the snowline elevation (SLE), are vital indicators of climate change and water availability in mountain regions. We examined the interannual and decadal changes in SCA and SLE in Nepal's Langtang Basin from 1988 to 2024. Using Landsat images and the Normalized Difference Snow Index (NDSI) on Google Earth Engine (GEE), we found that Annual SCA declined from ~200 km^2 in 1988 to ~128 km^2 in 2024, with a statistically significant trend of -3.7 km^2/year ($p = 0.001$). Snowline elevation rose by approximately +2.24 m/year ($p = 0.088$), indicating an upward shift of seasonal snowpack. These results indicate significant cryospheric changes in Langtang, consistent with regional warming trends. This study highlights the power of open-access satellite data and cloud platforms for monitoring remote mountain environments. Our research supports the International Year of Glacier Preservation (IYGP 2025) and the UN Decade of Action for Cryosphere Sciences (2025-2034).

Keywords: climate change, Google Earth Engine (GEE), Langtang Basin, Snow-Covered Area (SCA), Snow Line Elevation (SLE)

Introduction

Permanent snow and ice sustain glaciers, protect permafrost layers, and regulate water flow (Hock et al., 2019). Rising temperatures have shortened snowfall seasons, altered precipitation patterns, and accelerated snowmelt in mountains (Sun et al., 2024). As a result, warming has contributed to the retreat of snow and glaciers, resulting in decreased snow accumulation and alterations in the phase and distribution of the precipitation (Bolch et al., 2012). In the Himalayas, snow melt contributes up to 40% of streamflow (Chaulagain, 1970; Sasaki et al., 2024; Immerzeel et al., 2009). Understanding changes in snow and ice is critical for communities and ecosystems downstream that rely on meltwater (ICIMOD, 2023).

Satellite remote sensing consistently monitors Himalayan snowfields, which are often inaccessible and have sparse weather stations (Desinayak et al., 2022; Khan et al., 2024). Landsat, with high spatial resolution and reliable cloud masking, provides a strong basis for mapping perennial snow and ice (Khan et al., 2024) and verifying other satellite datasets (Painter et al., 2009; Tuladhar, 2006; Rittger et al., 2021). Comparison between Landsat and MODIS shows that accurate cloud masking is observed in Landsat for a snow-covered area (Stillinger et al., 2019). Therefore, we used Landsat imagery to assess changes in snow cover and elevation in Langtang Basin from 1988 to 2024.

With over 50% of its area covered by snow or ice, Langtang is especially sensitive to cryospheric changes (Pradhananga et al., 2024). According to Brown et al. (2014), glacier melt, snowmelt, and rainfall contribute 62%, 30%, and 8%, respectively, to total surface water in this basin. Our study examines rapid changes in Langtang's snowfields and raises awareness of their impact on livelihoods. This work supports the UN Decade of Action for Cryospheric Sciences (2025-2034) and the International Year of Glacier Preservation 2025.

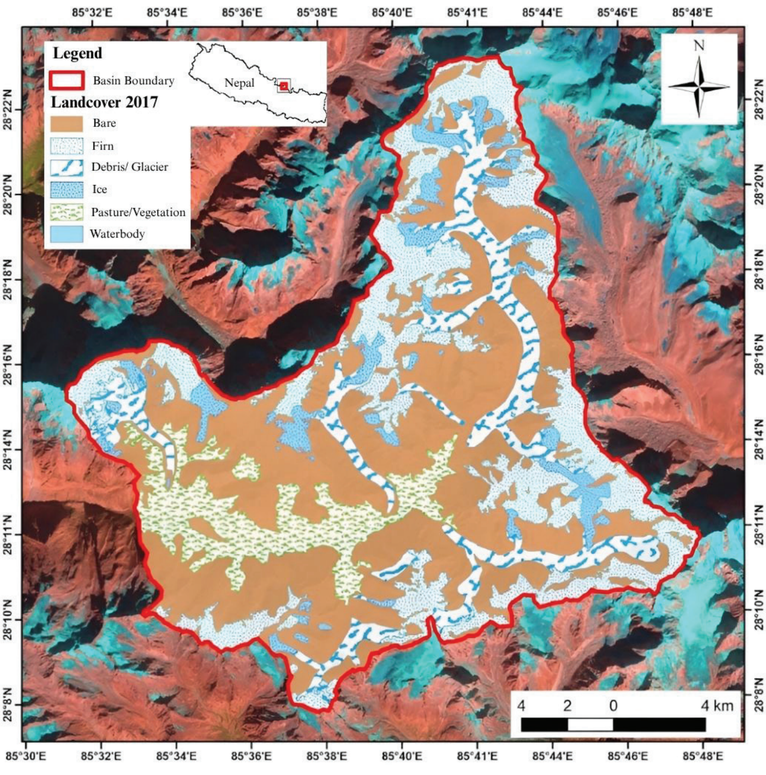
Materials and methods

Study area

The Langtang Basin (Figure 1) in central Nepal (28°08'–28°23' N, 85°35'–85°48' E) spans 354 km², with elevations ranging from 3,800 m to 7,234 meters above sea level (m a.s.l.). Approximately 53.5% of the basin is under glacier and snow cover (Pradhananga et al., 2024), and the mean slope is 26.7° (Immerzeel et al., 2012; Pradhananga et al., 2014; Zhou et al., 2014). Figure 2 provides a visual overview of the study area, including the Khimsung Glacier, a meteorological station at Kyanjing, a hydrometric station along Langtang Khola, and glimpses of the challenges local communities face in this high mountain environment.

Figure 1

Location and land-cover map (2017) of Langtang Basin



Note:

The basin boundary is shown by a red polygon.

Figure 2

Khimsung glacier, meteorological and hydrometric station

Note:

A. Khimsung Glacier, B. Kyanjing Meteorological Station, C. Langtang Khola Hydrometric Station, and D. A glimpse of local livelihoods and climate vulnerability

Climate

Langtang experiences a strong monsoon season from June to September, contributing ~80% of the average 622 mm annual precipitation as observed at the Kyanjing Meteorological Station (Figure 2b) of the Department of Hydrology and Meteorology (Wilson et al., 2016). June to August are the wettest, with persistent precipitation, where daily precipitation amounts generally do not exceed 20 mm/day. In contrast, September and October experience fewer rainy days but higher daily maximum precipitation. During the dry season (November to May), precipitation events are infrequent, primarily snowfall at higher elevations (Immerzeel et al., 2012; Ragettli & Miles, 2015). Precipitation is strongly altitude-dependent, where higher elevation receives more precipitation in comparison to the lower valleys.

Temperature peaks during July and August, and is coldest during December - February (Lamsal et al., 2017). From 1957 to 2002, the average temperature from October to June was 0.5°C, and 8.4°C during monsoon (Immerzeel et al., 2012). Warming and monsoonal precipitation increasingly fall as rain rather than snow, reducing accumulation and raising the snowline.

Methodology

Snow cover was mapped using satellite images in the visible band and the short-wave infrared

(SWIR) bands. This approach leverages the unique characteristics of snow, which has high reflectance in the visible band and strong absorption in the SWIR band. We applied the Normalized Difference Snow Index (NDSI) to identify the snow-covered area (Wang et al., 2022) as:

$$NDSI = \frac{R_{VIS} - R_{SWIR}}{R_{VIS} + R_{SWIR}}$$

Where, VIS = Visible Imagery

SWIR = Short-wave Infrared Imagery

R_{VIS} = Reflectance of the Visible Imagery

R_{SWIR} = Reflectance of the SWIR

We considered a snow threshold value of NDSI > 0.4, based on Choubin et al. (2019). We processed Landsat 5 (1987–2011) and Landsat 8 (2013–2024) surface reflectance data in Google Earth Engine (GEE). Images with <15% cloud cover were selected, clipped to the basin, and combined using median composites. The top-of-atmosphere (TOA) reflectance was computed using official scaling factors, and green and SWIR bands were used for NDSI mapping.

We visualized snow in white and non-snow land surfaces in a red-to-dark-red palette based on SWIR reflectance (Figures 3 & 4). A mosaic was created to highlight the snow-land separation. Trends in SCA and SLE were examined using p-values and Sen's slope; significance was set at $p<0.05$.

Surface reflectance values were transformed to the TOA reflectance using standard Landsat 5 and Landsat 8 scaling factors to improve cloud and surface assessments. For Landsat 5, NDSI was calculated using band 2 (green) and band 5 (SWIR1); for Landsat 8, bands 3 (green) and 6 (SWIR1) were used.

Data sources

Landsat 5 imagery (1987–2011) and Landsat 8 imagery (2013–2024), with a data gap in 2002 and 2012, were accessed in GEE. With a 16-day revisit cycle, yearly composites were made, and four decadal periods analyzed: 1988–1996, 1997–2005, 2006–2015, and 2016–2024. The data gap (2002 and 2012) remains a limitation, though interpolation across years reduces its overall impact.

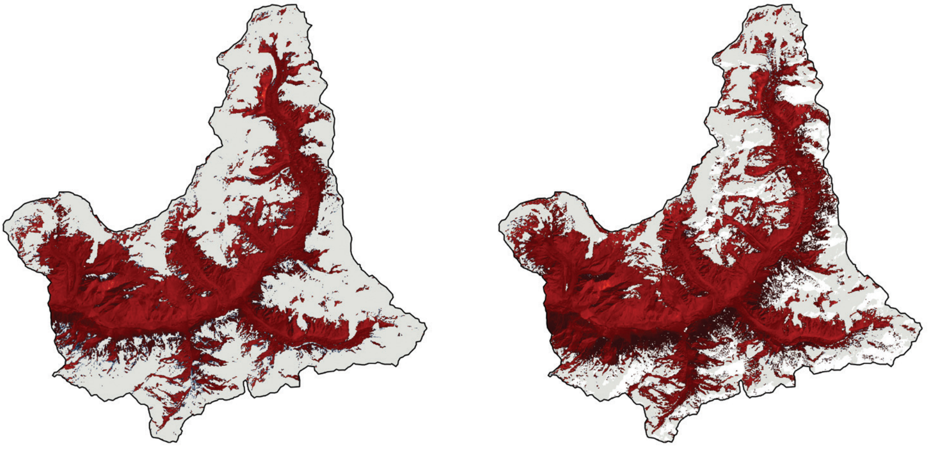
Results

Snow cover map of Langtang Basin

The snow cover maps (Figure 3) generated from Landsat Imagery illustrate notable spatial and temporal changes in snow distribution across the Langtang Basin. In 1988, the basin exhibited widespread snow coverage, particularly in higher elevation zones, with a total snow-covered area (SCA) of 200.4 km². In contrast, the 2024 map shows a significantly reduced snow cover extent of 128.2 km². This substantial decline of approximately 36% over the 36 years underscores the substantial retreat of snow-covered surfaces, likely due to the impacts of regional warming and changing precipitation and snow accumulation dynamics. The retreat is particularly visible at mid and lower elevations, with snow now concentrated primarily at higher altitudes.

Figure 3

Langtang Basin snow cover map



Note:

Snow cover map of 1988 (L) & 2024 (R).

Decadal snow-cover map

As shown in Table 1 and Figure 4, the snow cover area was relatively stable or even slightly increased in the 1990s, with a peak in the 1997–2005 period (240.7 km²). However, after 2005, there is a clear downward trend, with a 28% reduction from 1997–2005 to 2016–2024. The reduction is most evident in mid-altitude regions and valley floors.

Table 1

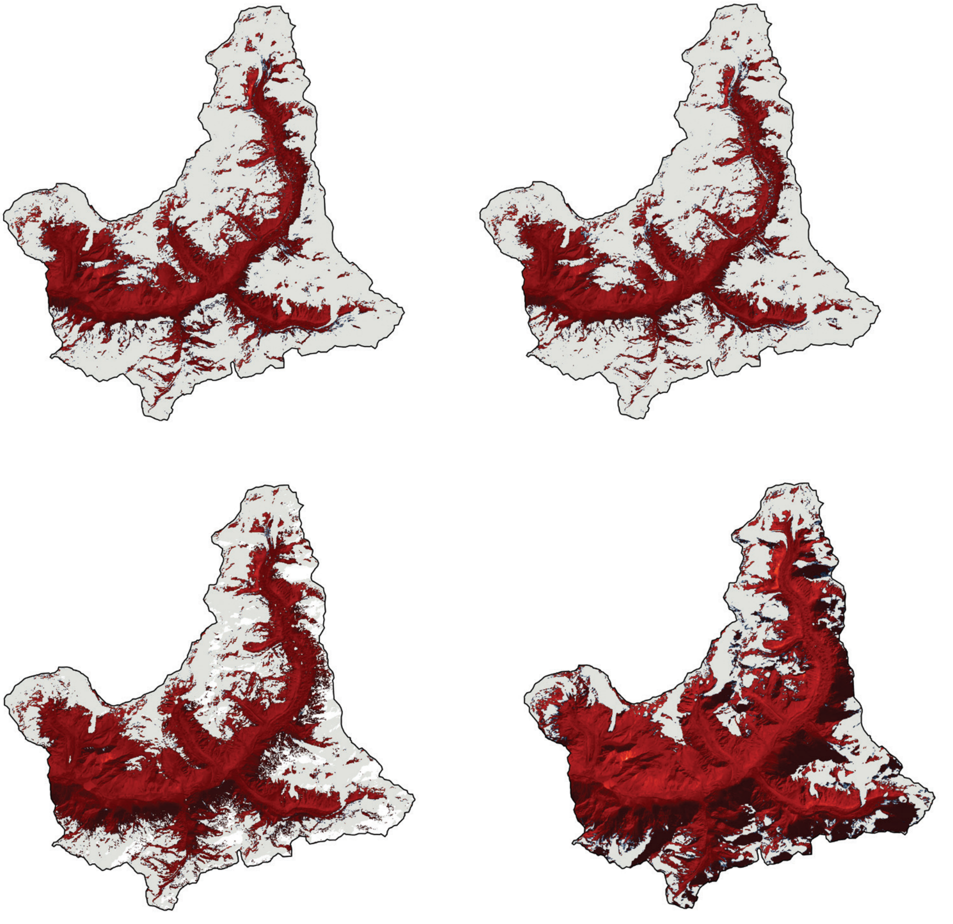
The median decadal snow-covered area of the Langtang Basin

Decade	SCA (km²)
1988-1996	229.3
1997-2005	240.7
2006-2015	175.8
2016-2024	154.5

This visual and quantitative representation highlights a shrinking snow-covered area and an increasingly exposed terrain, particularly at lower and mid-elevations. The reduction of snowfield area may significantly influence glacier mass balance, streamflow seasonality, and water availability in downstream regions.

Figure 4

Decadal snow cover maps of Langtang Basin



Note:

Decadal snow cover maps using Landsat imagery for (a) 1988 -1996, (b) 1997 - 2005, (c) 2006 - 2015, & (d) 2016 - 2024.

Snow cover area and snowline elevation graphs

Annual variations in SCA and minimum snowline elevation from 1988 to 2024 are presented in Figure 5. The analysis reveals notable interannual variability in snow cover extent, with frequent values below 200 km² after 2010. A statistically significant declining trend in SCA is observed ($p = 0.001$), at a rate of approximately 3.7 km² per year.

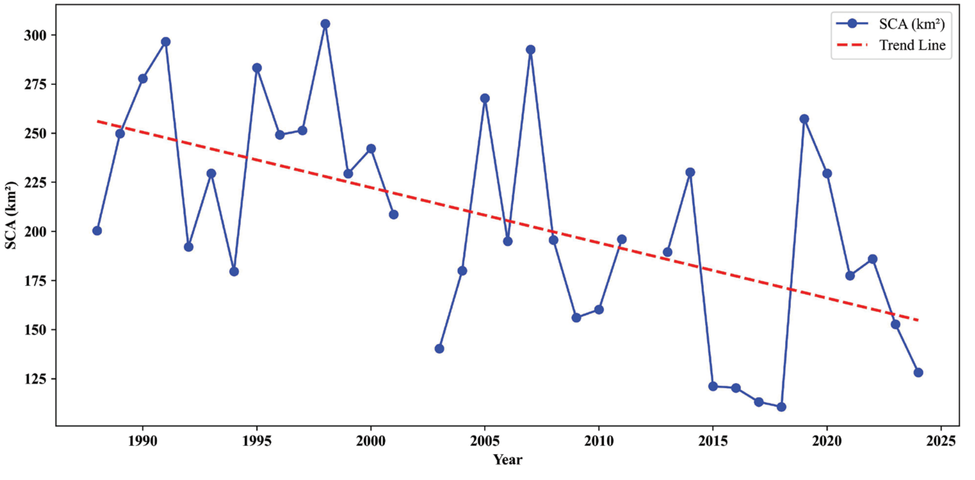
In contrast, the minimum snowline elevation has exhibited an upward trend, from around 4875 m in 1988 to over 5075 m in 2024, with a calculated rate of 2.24 m/year. However, this trend is not statistically significant ($p = 0.088$), likely due to data gaps (e.g., missing imagery in 2012) and cloud interference.

The graphs also reveal an inverse relationship between SCA and snowline elevation: years with lower snowline altitudes generally correspond to higher SCAs, and vice versa.

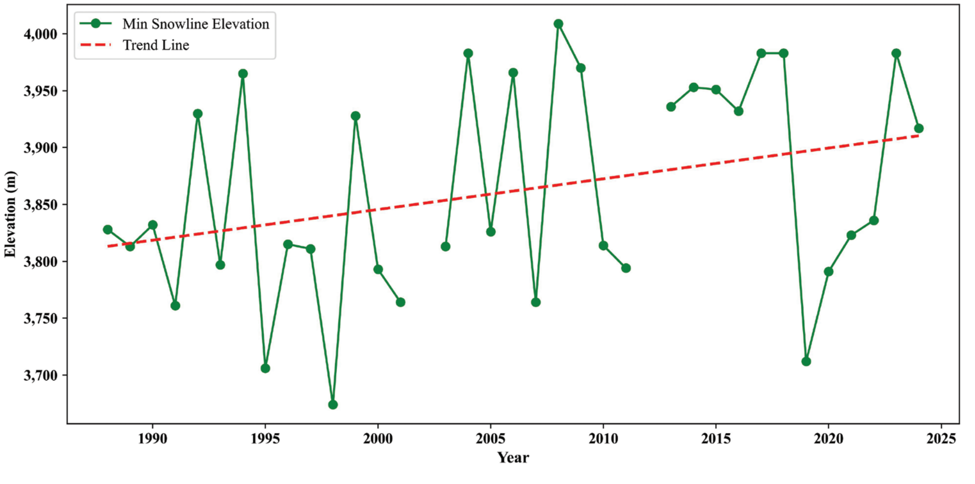
Figure 5

Snow-covered area and snowline elevation

A.



B.



Note:

A. Annual variation in snow-covered area, and B. Minimum snowline elevation (m a.s.l.) in the Langtang Basin (1988–2024).

Snow cover area and snowline anomalies

Figure 6 presents the anomalies of SCA and snowline elevation relative to the long-term means. The mean SCA over the study period was 230.2 km². Between 1990 and 2001, most anomalies were positive, indicating above-average snow cover, except in 1992 and 1994.

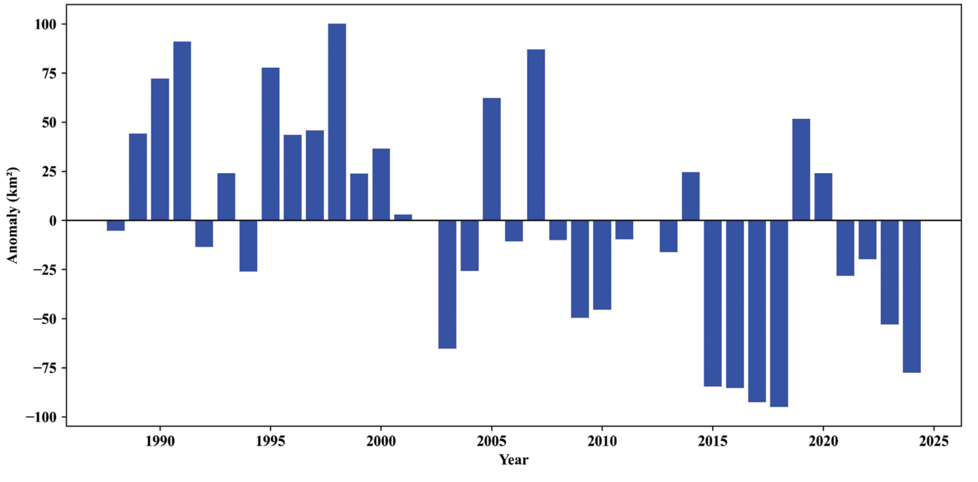
From 2003 onward, however, the anomalies are predominantly negative, indicating widespread snow cover loss.

The snowline elevation anomaly graph (Figure 6b) shows that from 1990 to 2002, the snowline was frequently below the mean, while from 2003 to 2024, positive anomalies dominate, suggesting an upward snowline trend consistent with warming conditions.

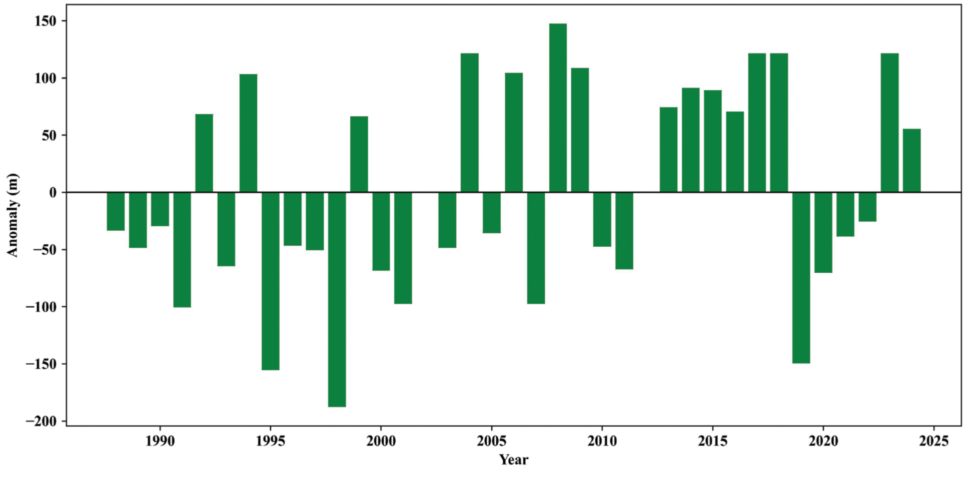
Figure 6

Snow-covered area and snowline elevation anomalies

A.



B.



Note:

A. Snow-covered area anomalies, and B. Snowline elevation anomalies in the Langtang Basin (1988–2024).

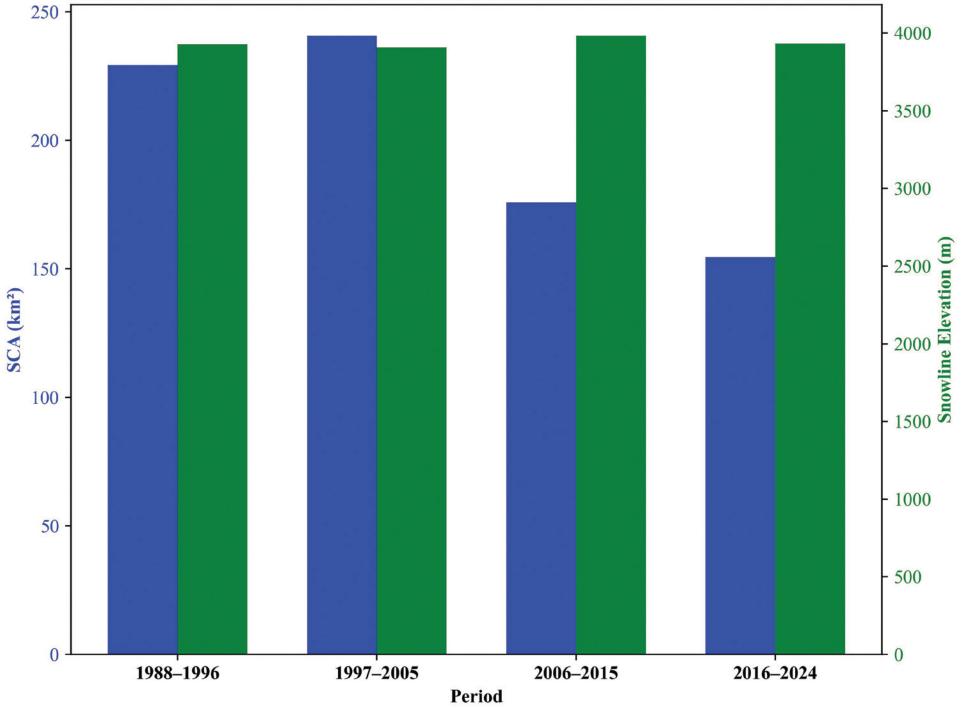
Decadal change

Figure 7 illustrates the decadal average values of snow cover area and snowline elevation. From 1988 to 1996, the basin had an average snow cover of 229.2 km² and a snowline elevation of approximately 4000 m. A slight increase in snow cover was noted in the 1997–2005 period (240.7 km²), with snowline elevation remaining relatively stable.

However, substantial reductions in SCA occurred in the last two decades (2006–2015 and 2016–2024), with averages below 200 km², while snowline elevation showed a gradual upward shift.

Figure 7

Decadal (1988–2024) trends in snow cover and snowline



Note:

A. Decadal (1988–2024) trends in snow cover area (blue), and B. Mean minimum snowline elevation in m a.s.l. (green).

These trends suggest a significant impact of climate warming, potentially enhanced by anthropogenic factors such as the combustion of biomass fuels. The loss of snow cover not only alters hydrological regimes but also poses risks to ecological systems and water-dependent communities.

Discussion

The analysis confirms a statistically significant declining trend in snow-covered area in the Langtang Basin from 1988 to 2024, with an average reduction of 3.7 km² per year. The snowline elevation shows an upward trend of 2.24 m per year, although it is not statistically significant ($p = 0.088$), likely due to data limitations and image gaps and cloud masking constraints.

These findings align with several past studies:

- Shrestha & Joshi (2009): Found decreasing trends in snow cover and increasing snowline elevations in the Langtang and Khumbu regions using Landsat and MODIS data. However, they warned of MODIS overestimations (~15%) and sensitivity to short image time series.
- Devkota & Shakya (2023): Reported peak snow coverage between February–April and declining snow duration (~40%) between 2000–2017, with greater reductions during the dry seasons.
- Gurung et al. (2017): Using MODIS, reported decreasing snow cover across the Hindu Kush Himalaya, including a decadal average of 4476.5 km² in the Gandaki basin from 2003–2012.
- Thapa et al. (2020): Validated a significant reduction in snow cover during winter and monsoon using the Mann-Kendall and Innovative Trend Analysis methods—findings echoed in this study.
- Khadka et al. (2020): Documented a post-monsoon snowline elevation trend of +33 m/year in western/central and +67 m/year in eastern Nepal (2003–2018). Their MODIS-based study also noted issues with cloud masking, which is relevant here as well.

Despite using high-quality Landsat imagery and GEE, limitations include in medium-resolution imagery:

- Gaps in temporal coverage (e.g., no Landsat data in 2012),
- Cloud masking issues (limited to <15% cloud cover, no image in 2002),
- Challenges in snowline detection in steep, complex terrain.

In mountainous basins like Langtang, logistical constraints and harsh climatic conditions further complicate ground validation. Moreover, the relatively constant decadal snowline in the maps may reflect limitations in accurately capturing snowline positions from medium-resolution imagery.

Conclusion

This study assessed long-term variations in snow cover area and snowline elevation in the Langtang Basin from 1988 to 2024, using Landsat satellite imagery and Google Earth Engine. The findings demonstrate a statistically significant decline in snow-covered area, decreasing at a rate of ~ 3.7 km²/year. Snowline elevation rose by approximately ~2.24 m/year, though the trend was not statistically significant ($p = 0.088$). The decline in snow at mid and lower elevations signals major hydrological and ecological shifts, with implications for water resources and disaster risk. The visual and quantitative results illustrate the increasing vulnerability of the cryosphere in the Himalaya and the importance of continued monitoring.

Despite limitations such as cloud interference and missing years, GEE and Landsat provide powerful tools for cryosphere monitoring. Future research should integrate higher-resolution, multi-sensor datasets (e.g., Landsat + MODIS + Sentinel) with in-situ validation to improve the robustness of snow trend analysis in mountain basins.

Acknowledgments

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