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Dynamics of Snow and Glacier Cover in the Upper Karnali Basin, Nepal: An Analysis of Its Relationship with Climatic and Topographic Parameters

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Abstract

Snow and glacier cover in the Upper Karnali Basin (UKB) are crucial freshwater reservoirs that support downstream ecosystems and human populations. This study uses remote sensing and GIS data from various sources, MODIS-derived land surface temperature, and ERA5 reanalysis climate datasets to analyze snow cover dynamics from 2002 to 2023/24. The results show a significant decrease in snow-covered area (SCA), with an annual decline of about 3.99 km². Seasonal variations indicate the most significant reductions during the monsoon period (July-September), where rising temperatures accelerate

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snowmelt. The analysis also establishes a strong negative correlation between snow cover and temperature ($r = -0.59$ to -0.77, $p < 0.05$), with warming trends disproportionately affecting mid-to-high elevation zones (3000-5000 m a.s.l.). Glacier basins exhibit consistent retreat, with the mean glacier area declining from 119.046 hectares in 2000 to 100.472 hectares in 2023, highlighting the impact of climate change. Additionally, snowline analysis demonstrates an upward migration, with the 10th percentile snowline increasing at a rate of approximately 5.16 m/year, indicating progressive snow loss at lower elevations. These findings emphasize the vulnerability of UKB's cryosphere to climate change, necessitating adaptive water resource management strategies. This will help mitigate impacts on hydrology, agriculture, and regional water security.

Keywords: Snow and glacier, Karnali, Himalayas, Remote sensing, Climate Change, Elevation-depended-warming, Snowline

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1. Introduction

Snow and glaciers in the mountains function as freshwater towers. Meltwater from mountain snow and glaciers releases water, providing a consistent supply for rivers and downstream ecosystems (Immerzeel et al., 2020; Wester et al., 2019; Pritchard, 2019). Snow and glaciers in the Himalayas play a crucial role and present opportunities for economic development and an improved quality of life for the local population(Pritchard, 2019). A decline in snow and glaciers will negatively affect water availability in the region (Krishnan et al., 2019). The alpine and downstream communities of Nepal, India, and China rely on snow and glacial meltwater for drinking, agriculture, livestock, electricity generation, and other needs (Bolch, 2007; Bookhagen and Burbank, 2010).

Furthermore, snow and glacial ice regulate regional and global climates by reflecting solar radiation, therby, contributing to the Earth's energy balance and influencing local weather patterns (Xu et al., 2009). Seasonal meltwater from glaciers and snow impacts ecosystems that provide habitats for numerous animal and plant species in the mountains. These organisms have adapted to the water availability from the mountain cryosphere. As a result, changes in snow cover and glaciers can disrupt entire ecosystems (Wester et al., 2019). On both local and regional scales, variations in the amount of snow and ice can contribute to changes in sea level, affecting coastal areas (Forster et al., 2021; Mimura, 2013; NOAA, 2013).

Snow-covered peaks and glaciers attract adventure tourism, while the glaciated landscape offers opportunities for nature-based aesthetic, recreational, and religious tourism (Anup, 2017; Nyaupane and Chhetri, 2009). Snow and glaciers are sensitive to climate change; shifts in their size and volume provide insights into broader climate trends and serve as visible indicators of environmental change.

There is growing concern that global warming is altering the cryosphere, with significant implications for human welfare and ecosystems (Elsasser and Bürki, 2002). Understanding how changes in snow and glaciers will impact future hydrology, water availability, and cryospheric hazards necessitates systematic,

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long-term assessment and monitoring. Historically, large-scale snow cover data were limited, especially in remote and less populated regions. However, advancements in satellite remote sensing since the 1970s have made snow cover mapping more accessible and routine. Accurate monitoring of snow cover is essential for managing water resources, promoting economic development, and mitigating risks associated with cryospheric disasters (Muhammad and Thapa, 2020). This is particularly critical in regions where snowmelt is a primary source of river discharge, such as the Himalayan river basins. Studies have revealed a significant reduction in snow-covered areas and accelerated glacial melting in the region over recent decades (Bajracharya et al., 2014; Bolch et al., 2012; Gurung et al., 2017; Andreas Kääb et al., 2012; Krishnan et al., 2019; Kulkarni et al., 2021; Mishra et al., 2014; Mool et al., 2001; Arun B Shrestha and Aryal, 2011). These studies emphasize the critical role of cryospheric changes in shaping the region's hydrology, affecting the magnitude and seasonality of drinking water supply, irrigation, and the country's energy production from hydropower. Integrating remote sensing data, ground-based observations, and climate models has been effective in assessing and predicting changes in snow and ice dynamics

A vast body of literature exists on Nepali Himalayan glaciers, glacier lakes, and glacier lake outburst floods (GLOFs), offering insights into cryosphere dynamics and climate variability since the 1960s(Bajracharya et al., 2008; Hall et al., 2002; A Kääb et al., 2005; Maheswor Shrestha et al., 2012; Zemp, 2006). However, most studies focus on the central and eastern Himalayas of Nepal, leaving the mid-western and far-western regions underexplored due to their remoteness, limited accessibility, and lack of attention. While global and regional glacier inventories cover these areas in-depth, more focused studies of snow and glacier cover change using high spatial resolution detailed studies ≤ 30 m, Elevation Dependent Warming (EDW) and snow cover trend are limited(Bajracharya et al., 2014; Bishop et al., 2004; Heid and Kääb, 2012). Integrating glaciers, glacier basins, and snow cover while linking them to climate change is also under-examined.

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Bridging this spatial knowledge gap through focused research on cryosphere dynamics in these regions is crucial. It will enhance the understanding of long-term changes and provide evidence-based data to inform policies on ecology, hazards, water availability, and food security, benefiting both alpine and downstream populations.

The Karnali Basin is the largest river basin in Nepal, home to ~2.5 million people (www.censusnepal.cbs.gov.np). The Karnali River system drains an area of 40,780 km² over the Chisapani gauge station. The snow and glacier-fed waters in the basin provide irrigation for millions living within and across the Indo-Nepal border, especially during the dry season. Additionally, snow and glaciers supply moisture and water for agro-pastoralism, the primary livelihood of local communities in alpine regions. Despite their significant freshwater sources, high ecological value, and potential for hydropower and tourism-based prosperity, snow and glaciated areas in the Karnali Basin have remained a frontier for cryosphere studies.

While extensive literature exists on snow, glaciers, and glacial lakes in the central and eastern Himalayas of Nepal, as well as in the Indian Himalayas and adjacent Tibetan Plateau, the findings of these studies cannot be reliably applied to the Karnali Basin due to differing climatic regimes and trends in various geographical settings. Understanding the impacts of cryosphere change on water resources necessitates studies specific to the status and dynamics of the cryosphere in the Karnali Basin. Additionally, integrating MODIS data with high temporal but lower spatial resolution and Landsat series data with low temporal but higher spatial resolution will enhance our understanding of snow and glacier changes, revealing trends in snow cover and their connections to topography, glacier basins, and climate fluctuations.

2. Study area

The Upper Karnali Basin, located between 28.64-30.68° N and 80.64-83.54° E, covers 22,577 km2 and includes sub basins drained by the Humla Karnali, Mugu Karnali, Kawari, and Tila Nadi rivers (Ghimire

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et al., 2024) (Figure 1). The elevation ranges from 340 m to 7030 m, with an alpine zone above 4000 m consisting of snow, glaciers, and bare rocks. The climate varies from Polar Tundra in the glacier region to subtropical, temperate, and cold climates below 4000 m, with mean annual temperatures ranging from 27ºC to <-12ºC and precipitation from 1000 to 800 mm annually.

The Upper Karnali Basin features a diverse landscape of snow-covered glaciers, valleys, permafrost, alpine meadows, and forests, along with a rich variety of flora and fauna. It is a cultural blend of Khas and Tibetan traditions and is a growing tourist destination, including a stop on the Kailash Mansarovar pilgrimage route. The basin has a population of approximately 816,941 people with a density of 36.2 persons/km2, residing in 4,395 settlements primarily below 4000 m. The Human Development Index in the area is below the national average at 0.49.

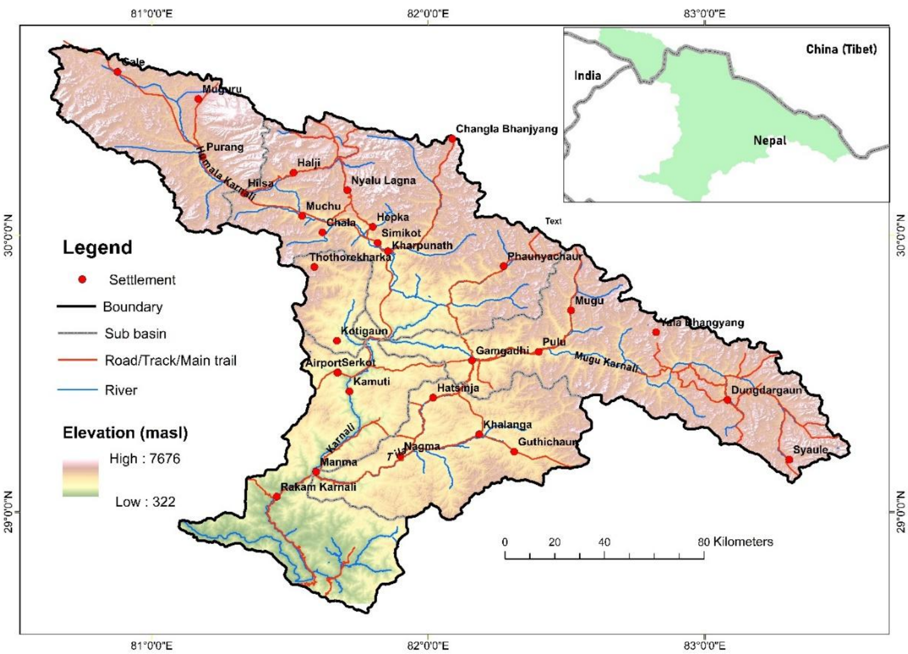

Figure 1. Location of the Upper Karnali Basin.

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3. Data Sources and Method

To achieve its objectives, the study employed remote sensing technology alongside various data sources. It employed coarse-to-moderate-resolution optical and thermal satellite imagery from MODIS Aqua and Terra, Landsat TM5, ETM 7, and OLI 8, accessed through the Google Earth Engine platform(Gorelick et al., 2017; Hall et al., 2002). This imagery was used to gather time series data on snow and ice cover and land surface temperature.

To generate a snow cover map using Google Earth Engine (GEE) and Landsat data, we began by accessing the GEE Code Editor. We loaded the relevant Landsat Image Collection (Landsat 5, 7, or 8) and filtered the data by specifying the time range, area of interest (Upper Karnali Basin), and acceptable cloud cover. Imageries were preprocessed by masking clouds using the Quality Assessment (QA) bands (pixel_qa for Landsat 5/7 or QA_PIXEL for Landsat 8). Then Normalized Difference Snow Index (NDSI) was then calculated using Green and Short-wave infrared bands (Gorelick et al., 2017; Hall et al., 2002). Then, a threshold NDSI > 0.4 was applied to isolate snow cover pixels from others. Finally, we exported the snow cover map as a GeoTIFF file for further overlay analysis with sun-basin and microglacier basins.

MODIS snow cover data (MOD10A1) was processed using Google Earth Engine (GEE)(Hall et al., 2002) for the Upper Karnali region. The cloud-masked snow cover data was classified into four seasonal composites: January–March, April–June, July–September, and October–December. Elevation bands were defined based on the SRTM DEM and categorized as below 3000 m, 3000–4000 m, 4000–5000 m, and above 5000 m. Zonal statistics were applied to extract the frequency of snow cover for each elevation band and subbasin. The snow-covered area was calculated using a threshold-based binary mask. The results were aggregated into a structured dataset, revealing seasonal snow distribution and variations across elevation zones and watersheds, thus facilitating hydrological analysis.

The land surface temperature (LST) was also downloaded from the Application for Extracting and Exploring Analysis Ready Sample (AppEEARS) platform. AppEEARS is a NASA-supported platform developed to easily access, subset into specified areas, and analyze climate and environmental data. Temperature and precipitation data, including maximum and minimum values, were procured from the Government of Nepal's Department of Hydrology and Meteorology and open-access platforms such as the ERA5 Reanalysis.

The time series glacier data compiled by Ghimire et al. (2024) (submitted) was included in the study. The same lead author of this manuscript was responsible for the research paper. In summary, glacier polygons for the years 2000, 2010, and 2023 were mapped using high-resolution images (from Google Earth, Bing Maps, and Rapid Eye) from 2000 and 2023 to maintain temporal consistency. Snow and glaciers were identified based on their bright spectral features, smooth textures, and shadows on nearby terrain. Landsat composites (both true and false color) and band ratios like NDSI improved the visibility of snow and ice, while altitude and topographic data derived from DEM highlighted potential glacier regions. Outlines from the Randolph Glacier Inventory (RGI)(Pfeffer et al., 2014) and ICIMOD (Bajracharya et al., 2014) were used as reference points, while ground-truth observations and additional datasets helped validate the findings. This comprehensive approach ensured precise delineation.

3.1. Delineation of the glacier basin

The boundaries of glacier basins were defined to evaluate the snow cover fraction in glacier-drained areas. Glacier basins are regions that encompass both central and sub-glaciers fed by moving ice and snow. Their boundaries are marked by the main glacier's terminus. The process involved multiple steps to ensure precision.

Initially, the Glacier Inventory map referenced earlier served as a fundamental resource. High-resolution imagery and ESRI's topographic maps in ArcGIS 10+ supplied intricate spatial data. A 12.5 m DEM was utilized to extract drainage networks, produce contour lines, and generate hillshade maps, which

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improved the visualization of the divides between glacier basins. These components were vital for pinpointing the glacier terminus and outlining glacier head basins. This holistic approach, merging topographic analysis, remote sensing, and geospatial techniques, facilitated the precise delineation of glacier basins for comprehensive evaluations of snow cover fraction.

3.2. Limitations

This study encountered limitations due to significant cloud cover, making cloud-free conditions infrequent for Landsat during the pre-monsoon and monsoon periods. Consequently, snow cover data from Landsat was accessible only for the months of January through March and October through December in the Upper Karnali sub-basins. Nonetheless, all four seasons were examined for micro glacier basins where data was dependable. To address this limitation, MODIS (MOD10A1) data was employed. This method also enabled a comparison between the data obtained from Landsat's higher spatial resolution (30 m) but lower temporal resolution (16 days) and MODIS's daily high temporal resolution with lower spatial resolution (500 m).

4. Result

4.1. Snow or ice cover trend and variability: Annual and seasonal

The total snow cover across the Upper Karnali Basin (22,546 km²) from 2002–2024 averages 872 km², with a standard deviation of 147 km², indicating moderate variability (Table 1 and Figure 2). The minimum recorded snow cover is 424.25 km²; about 25% of the recorded snow cover observations are at or below 640.32 km². The average snowfall from January–March is (1528 ±333 km^2), followed by April-June (881 ± 212 km^2) and October–December (862±373 km^2), respectively. July to September witnessed the lowest snow cover area, i.e., 212 ±38.3 km^2.

Snow cover data highlights significant year-to-year changes in every quarterly season with varying directions and magnitude of trends, evidenced by correlation, the Kendall tau test, and Sen's slope. The annual average SCA shows, although not significant, a decreasing trend (p = 0.535), with Sen's Slope

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estimating a loss of ~3.99 km2/year, which indicates a gradual decline in snowpack over two decades. Seasonally, the July–September period exhibits the statistically significant steepest drop in snow cover (Sen's Slope = -2.87, p = 0.00). This period is snow ablation, where the summer monsoon brings warmer temperatures. In mid-latitude regions, the precipitation occurs more as rain than snow, resulting in accelerated snowmelt. While January–March shows a decline (Sen's slope =8.63km/year), it lacks statistical significance (p = 0.523), suggesting year-to-year winter variability in snowfall or early melt. Similarly, no significant trends were detected in April–June. Interannual variability is evident with peaks and lows of snow and ice coverage (Figure 2). Episodic snow coverage in 2015, 2020, and 2022 (January–March), 2015 and 2019 (April–June), 2009, and 2021 (October–December), high episodic heavy snowfall years. However, these anomalies do not counterbalance long-term declines. Compared to seasons, annual snow coverage's inter-annual variability is relatively low, i.e., with a 16% coefficient of variation (CoV)–ratio of the standard deviation to the mean.

Table 1. Snow cover descriptors and changes by seasons

Descriptors	January–March	April–June	July–September	October–December	Annual average
Mean	1528	881	217	862	872
Median	1569	858	210	739	886
Std. dev.	333	212	38.3	373	147
Minimum	1025	503	169	340	514
Maximum	2167	1358	298	1737	1055
Skewness	0.211	0.47	0.937	0.509	-0.867
25 th Percentile	1270	751	191	538	777
50 th Percentile	1569	858	210	739	886
75 th Percentile	1689	1025	229	1126	991
Correlation	-0.087	-0.069	**-0.610**	-0.251	-0.274
Kendall's Tau	-0.091	0.013	**-0.541**	-0.134	-0.100
P value	-0.523	0.95	0.00	0.398	0.535
Sen's slope	-8.63	-3.14	-2.87	-13.21	-3.99

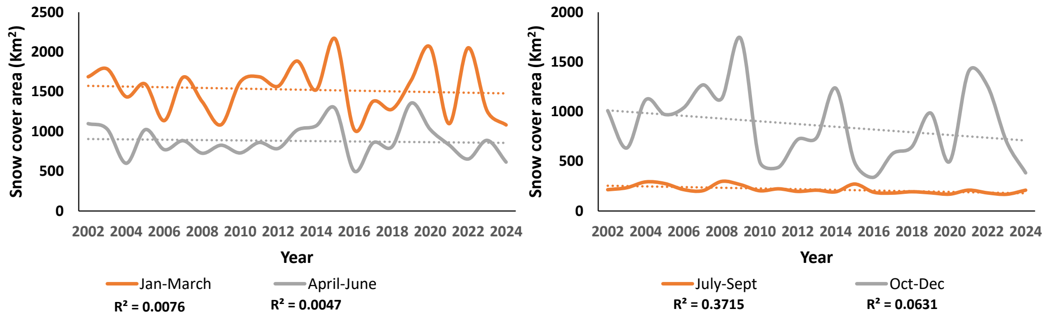

Figure 2. Snow cover trend in Upper Karnali Basin in different seasons.

4.2. The relation among snow cover, temperature, and precipitation

There is some spatial variation in the temperature trend, although negative correlations dominate most of the 204 sampled locations in all seasons except for the months April–June (Figure 3). The average rainfall across the 204 locations also shows a declining trend in all seasons except for June–July (Figure 4). The effect of precipitation on snowfall may influence the predominance of negative temperature correlations over time.

We generalized temperature data derived from MODIS Terra (MYD11A1) and Aqua (MOD11A2) Land Surface Temperature (LST), processed through AppEEARS, along with precipitation data sourced from the ERA5-Land reanalysis by ECMWF (Hersbach et al., 2020), collected from 204 locations across four different periods to examine the relationships between snow cover, temperature, and precipitation (Figure 5). The snow-covered area shows a strong to moderate negative correlation ($r = -0.59$–0.77, $p < 0.05$) with temperature across all seasons. Conversely, precipitation has a positive correlation ($r = 0.55$–0.59, $p < 0.05$) with snow cover for January–March and October–December, while during the remaining months, it shows a moderate negative correlation with negative trends. Precipitation and temperature display a negative correlation for January to March–October to December; during the summer months (April–September), these climatic variables also exhibit a positive correlation.

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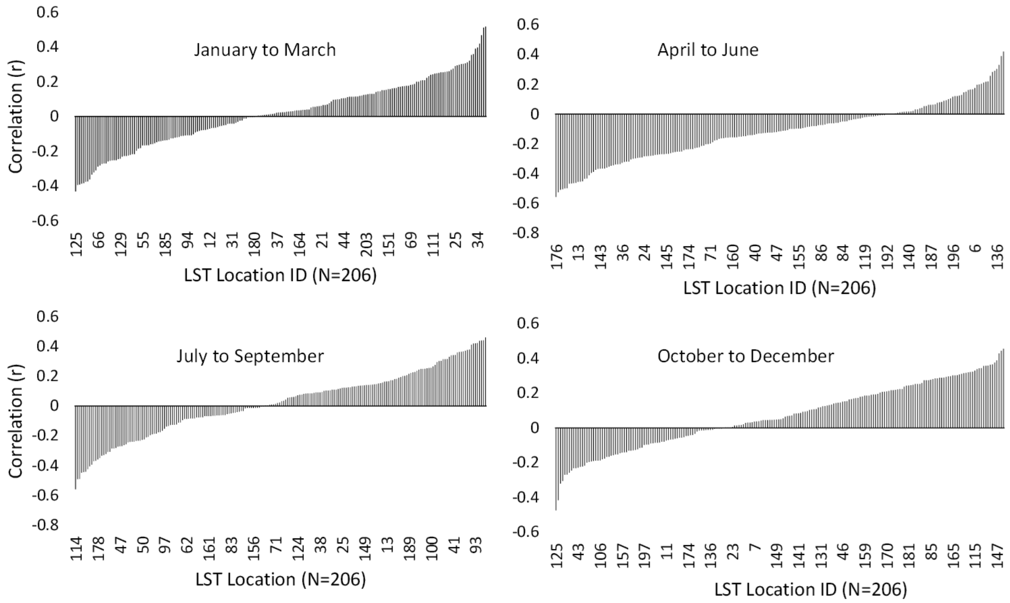

Figure 3. The correlation (r< -0.40 or <0.40, P<0.05) illustrates the temperature trend directions at various sites between 2000 and 2024 (Source: MODIS Terra and Aqua MOD11A2, MYD11A1, AppEEARS).

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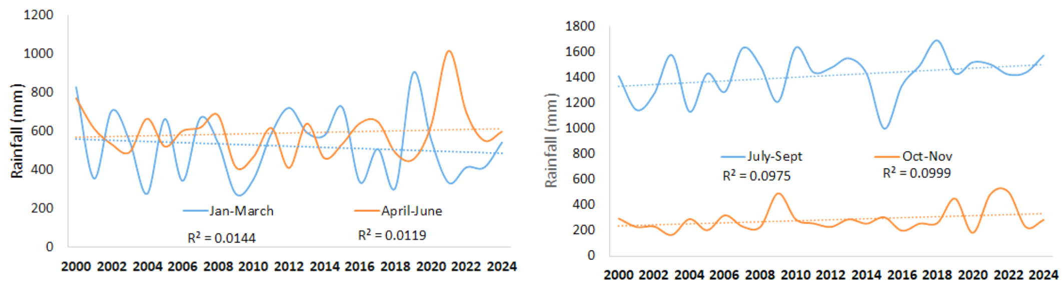

Figure 4. Yearly rainfall trends across various periods. Precipitation data was collected from the ERA5-Land reanalysis by ECMWF (Hersbach et al., 2020) from 204 locations across four different periods.

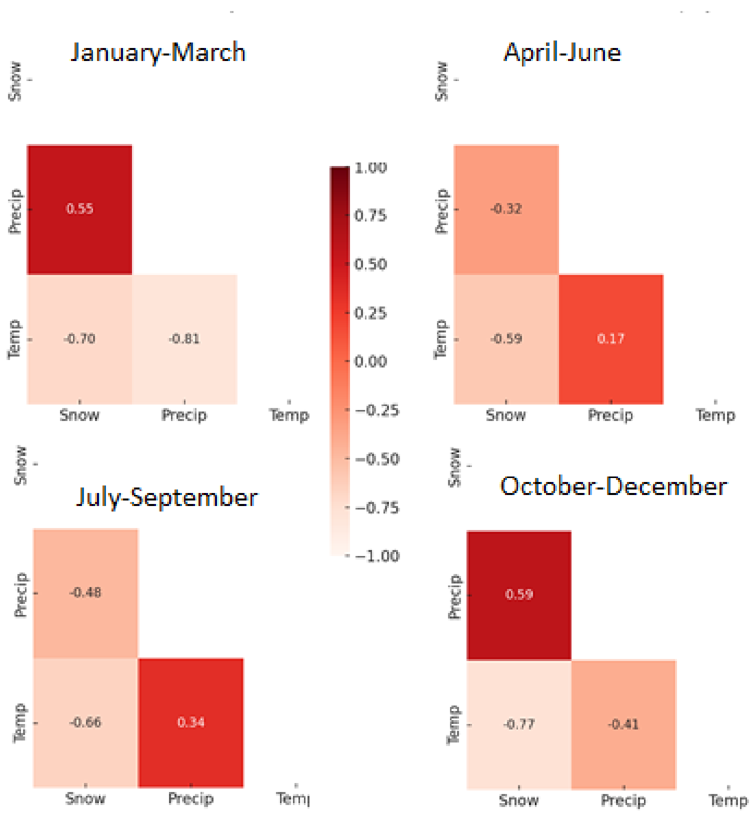

Figure 5. Relationship among snow, temperature, and precipitation

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4.3. Snow cover changes in sub-basins using Landsat series data

Due to the unavailability of Landsat-derived reliable snow and ice data in pre-monsoon and monsoon due to significant cloud coverage (as mentioned in section), only two seasons, January–March and October–November were considered. These seasons correspond to snowfall as precipitation that contributes to snow accumulation.

Examining snow cover patterns in the Upper Karnali Basin (UKB) sub-basins for two seasons January–Febraury and October–December reveals notable seasonal and spatial differences (Table 2). During January-February, Humla Karnali has the largest average snow cover at 3,336 km^2, followed by Mugu Karnali at 1,864 km^2 and China Karnali at 1,478 km^2, while areas downstream like Tila and Kawari have very little coverage (less than 350 km^2). There is significant variability in snow cover, particularly in Tila and Downstream Karnali, which has a coefficient of variation above 50%, indicating inconsistent snowfall from year to year from January–March, although associated with a significant negative correlation, i.e., $\geq$ -0.37 ($p<0.1$) (Figure 6). The skewness of the temporal distribution is moderately negative, which does not affect the correlation, which is negative for all the basins, indicating a declining trend.

Conversely, the October-December season has lower average snow cover (823 km^2) with strong fluctuations (e.g., 1570–227 km^2 and CoV=55%). Strong variability (CoV) is observed for all basins, particularly China Karnali, Tila and Downstream Karnali, the variability is strongest. The skewness is moderate, except Downstream Karnali and correlation values are reliable and indicate a declining trend. However, Downstream Karnali, in spite of high variability, indicates a statistically significant negative r value, i.e., -0.47 ($p<0.05$) (Figure 6).

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Table 2. Descriptive statistics of snow cover across sub-basins for two seasons (January-March and October-December) and the time series correlation from 2002 to 2024.

Descriptor	January - March							October-December						
	China Karnali	Humla Karnali	Mugu Karnali	Tila	Kaweri	Down strea m	Seasonal average	China Karnali	Humla Karnali	Mugu Karnali	Tila	Kaweri	Down stream	Seasonal average
Mean	1478	3336	1864	351	294	41.9	1227	854	2057	1442	332	204	48.1	823
Median	1420	3667	1827	346	308	39	1239	754	2159	1301	288	190	40.2	781
Standard deviation	501	597	645	184	86.2	24	311	622	1163	862	227	112	44.7	457
Coefficient of variation (CoV in %)	33.90	17.90	34.60	52.42	29.32	57.28	25.35	72.83	56.54	59.78	68.37	54.90	92.93	55.53
Minimum	552	1904	887	50.1	121	5.74	612	67.2	166	226	44.3	35.2	3.28	227
Maximum	2317	4009	3056	691	420	93.5	1642	2092	4074	2868	716	434	185	1570
Skewness	-0.707	-0.488	-1.29	-0.69	-0.469	-0.763	-1.1	0.533	-0.016	0.231	0.347	0.204	1.43	0.202
Correlation (r<-0.44 and r>0.44, p<0.05	-0.16	-0.18	-0.10	0.12	-0.37	-0.41	-0.14	-0.16	-0.07	-0.23	-0.17	-0.13	-0.47	-0.17

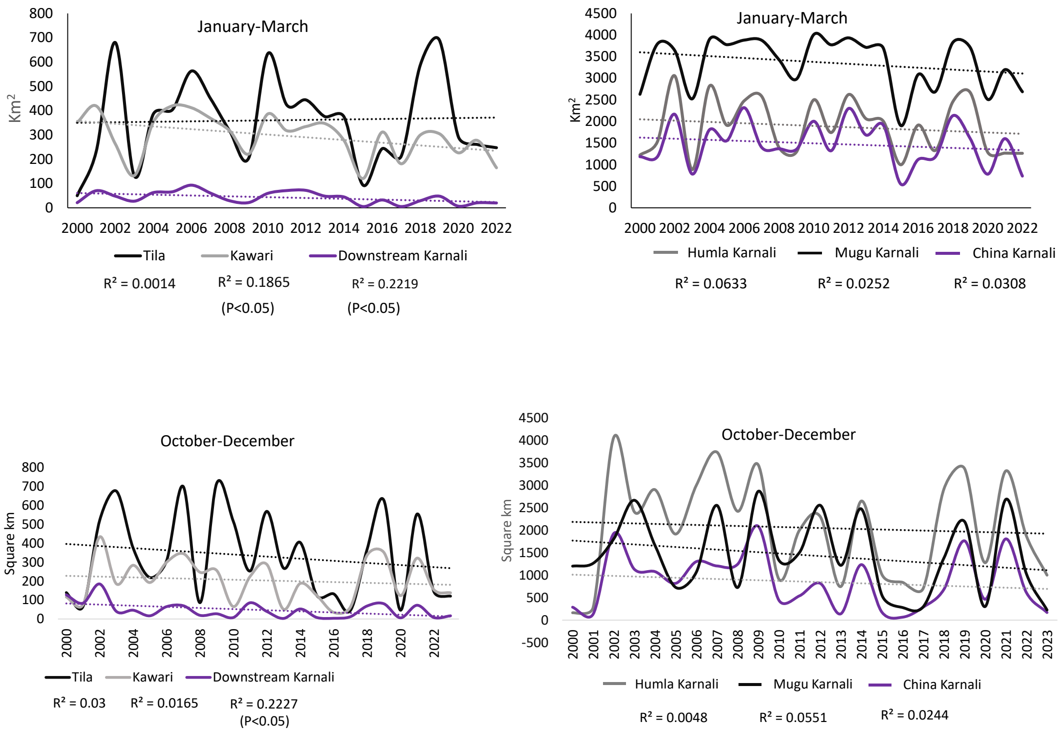

Figure 6. The snow cover trend in the Upper Karnali Basin varies across different sub-basins from January–March and from October–December.

4.4. Snow cover dynamics across elevation zones

The dynamics of snow cover across elevation zones, categorized in 100-meter intervals from ≤2000 m to ≥6500 m, reveal remarkable elevation-dependent patterns in correlation and variability (Figure 4). Snow cover in lower elevation zones shows a weak positive correlation (0.12-0.43), suggesting a marginal increase. However, pronounced interannual variability (CoV ~ 41-43%) is likely driven by fluctuating temperature and precipitation regimes(Pendergrass, 2020).

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Above 2300 m a.s.l., correlations shift to weak negative correlations (up to 5000 m a.s.l., r = 0.05-0.17) and moderate correlation upto 4800 m, then after, reaching peak negativity at 6100-6200 masl (r = -0.56), indicating a significant decline in snow cover over two decades (Figure 7). This trend aligns with the impacts of global warming, where rising temperatures disproportionately affect higher elevations, accelerating snowmelt and reducing accumulation (Shaoting Ren et al., 2023; Shen et al., 2021; Naegeli et al., 2019). The mean snow cover increases with elevation, showing a marked rise from 3300 to 6500 m a.s.l.. or above, except between 5000-5000 m a.s.l.. which exhibits a gradual rise of snow cover.

Above this point, the mean snow cover area rises sharply, coinciding with glaciers and permanent snow zones. In contrast, the CoV increases with elevation up to 3100 m a.s.l.. and then trends sharply downward from 3100 m a.s.l.. to 6500 m a.s.l.. and beyond. This pattern indicates a decline in interannual variability alongside increased negative correlations. The low inter-variability implies a reliable declining trend in snow cover elevation.

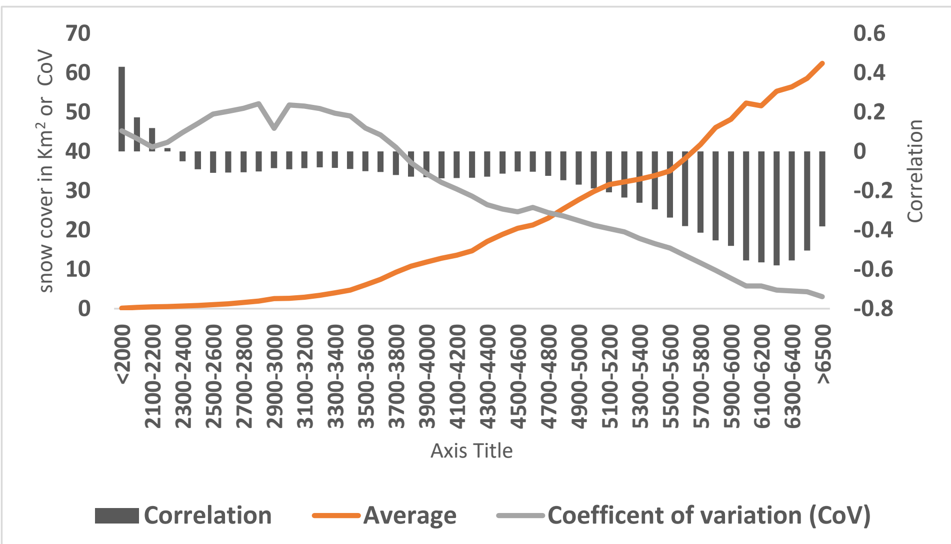

Figure 7. The average, coefficient of variation, and correlation of snow cover area across various elevation bands.

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To examine the relation between temperature and snow cover, the elevation bands were regrouped into seven broader bands: below 2000, 2000–3000, 3000–4000, 4000–5000, 5500–6000, and above m a.s.l... Figure 5 shows that the temperature has risen in all elevations. The temperature trend from 2002 to 2024 across elevation bands in the Upper Karnali Basin, as evidenced by Sen's slope (Figure 8, Table 3), shows a general increase, with the highest rate of change observed at lower elevations (<1000 m: 0.0765°C/year). Mid-elevations (1000-2000m: 0.0576°C/year) and high elevations (5000-5500m: 0.0643°C/year) also exhibit warming. However, statistical significance (P-value) weakens at higher elevations. This warming accelerates glacier retreat, reducing snow cover and impacting hydrology, leading to declining glacier-fed water supply and altering river flow patterns in the Upper Karnali Basin.

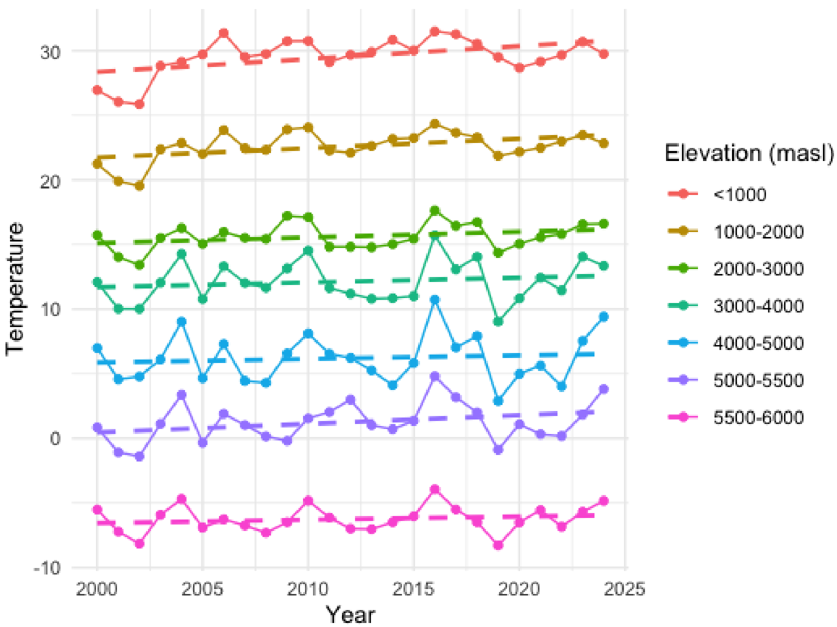

Figure 8. Temperature trend between 2002 and 2024 for different elevation bands

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Table 3. Rate of temperature change in different elevation between 2000-2024)

Elevation bands (m a.s.l.)	Sen's slope	P Value
<1000	0.0765	0.052
1000-2000	0.0576	0.058
2000-3000	0.0390	0.168
3000-4000	0.0410	0.528
4000-5000	0.0198	0.833
5000-5500	0.0643	0.154
5500-6000	0.0287	0.414

Figure 9 shows a strong negative correlation between land surface temperature and snow cover across elevation bands in the Upper Karnali Basin. Tau values range from -0.43 to -0.79, indicating that as temperature rises, snow cover declines significantly. The correlation is strongest between 3000-5000 m a.s.l.. (Tau = -0.77, -0.79) and 5000-5500 m a.s.l. (Tau = -0.75), with all p-values <0.01, confirming statistical significance. Even at 5500-6000 m a.s.l. (Tau = -0.43, p = 0.00353), snow cover continues to decline. The impact is most severe at mid-to-high elevations, where warming accelerates snowmelt and glacier retreat. This trend threatens water availability in the Upper Karnali Basin, affecting river flows, agriculture, and hydropower. The findings highlight the vulnerability of high-altitude regions to climate change, with rising temperatures disrupting the region's hydrological balance. Continuous warming will likely exacerbate glacial retreat, reducing freshwater storage and increasing water-related risks for downstream communities.

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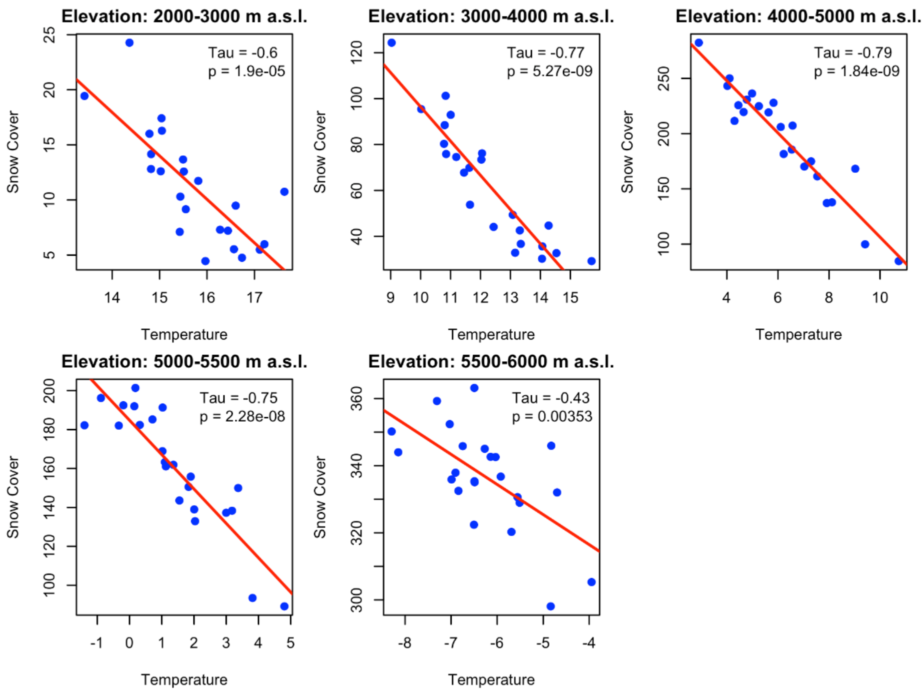

Figure 9. Relationship between snow cover and temperature (Celsius) across elevation zones in the Upper Karnali Basin (2002–2024).

4.5. Snow cover the trend in Glacier Basins (Landsat data).

We examined snow cover trends in glacier basins containing at least a glacier in 2000, greater than 10 hectares (# 735), which are crucial for assessing glacial status, water security, and climate change impacts (Table 4). The minimum altitude of the glacier basin where all tributary glaciers meet was considered an outlet of glacier basins. The rationale behind selecting glacier basins as the unit analyzing the snow cover trend is that glacier basins are the primary source of glacier mass accumulations. In these basins, snowfall restocks ice lost to melting, contributing to glacier stability and sustenance. Reduced snow cover in the glacier basins accelerates negative mass balance, a state where melting exceeds accumulation, leading to glacier retreat. These glacier basins are at a minimum altitude above 4000 m a.s.l. with an average of ~5100 m a.s.l.. Twenty-five and 75 % lie below 4800 and 5330 m a.s.l., respectively. Besides other meteorological parameters, current temperature trends and albedo patterns play a critical role in glacier mass balance (Ye and Tian, 2022; Dowson et al., 2020). Higher temperatures directly increase the snow melting rate, and a decrease in reflectivity of solar radiation leads to more solar radiation being absorbed by the glacier surface, leading to accelerated melting and a negative mass balance(Shaoting Ren et al., 2023). Declining permanent snow cover in the glacier basin disrupts the glacier mass balance, affects the glacier persistence, alters the water availability, and accentuates the climate-driven environmental changes.

The data reveals a significant decline in glacier area across 734 glacier basins between 2000 and 2023 (able. The mean glacier area decreased from 119.046 ha in 2000 to 100.472 ha in 2023, reflecting an average loss of 18.574 ha per basin. The total glacier area shrank by 13,633.163 ha, indicating widespread glacier retreat. The percent of glacier area to total basin area declined from 53.23% in 2000 to 44.93% in 2023, indicating a relative reduction in glacier coverage. Statistical tests show high skewness (>3.9), suggesting that a few large glaciers dominate the dataset. The Shapiro-Wilk test ($p < .001$) confirms a non-normal distribution.

Table 4. Change in glacier area between 2000 and 2023.

Glacier basin count (N=735)	Glacier basin Area (hectares)	Glacier area (hectares)		Difference in glacier area (hectares)
		2000	2023	
Median	101.4	52.8	39.7	-10.0
Mean	223.6	119.0	100.5	-18.6
Std. Dev	368.1	187.1	169.9	27.2
Skewness	4.6	4.0	4.0	-4.0
Sum	164140.9	87379.9	73746.8	-13633.2

The glacier area has declined across all basin directions from 2000 to 2023, with the basins oriented toward North (N), Northwest (NW), and Northeast (NE) experiencing the largest losses, totaling -6,126.9 hectares (Figure 10). Eastern (E), Northeast (NE), and Southwestern (SW) glaciers also show significant reductions, although less severe.

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The southern (S) and southeastern (SE) basins experienced significant shrinkage, indicating a widespread retreat. The negative differences across all directions confirm a consistent loss in glacier coverage, likely due to rising temperatures and decreased snowfall. These trends emphasize the ongoing effects of climate change on glacier-fed regions.

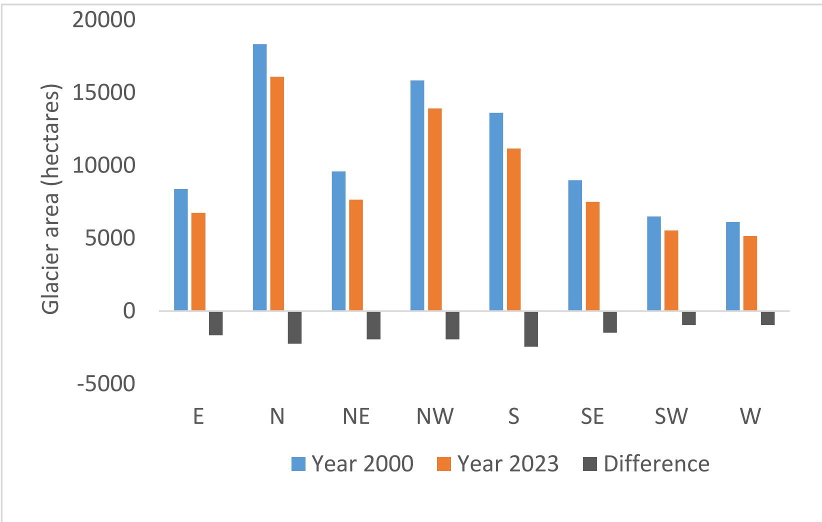

Figure 10. Change in glacier area in glacier basins by directions between 2000 and 2023.

Analysis of snow cover trends indicates that around 63% of glacier basins (n=735) demonstrate negative correlations from January to March. Among these, glacier basins with a correlation (r) value less than -0.44 ($p<0.05$) represent 16.3% of the total (Figure 11, 12, and 13). Basins with moderate negative correlations, ranging from -0.44 to -0.30, constitute approximately 19% of the overall total. Additionally, 47% of basins show a positive correlation, with 3% being statistically significant and 13% displaying a moderate correlation. The numerous glacier basins that exhibit negative correlations may suggest a broader regional trend of declining snow cover over time during winter (January to March). See Figure 8.

In the same way, during the months of May, June, and July, all 15 glacier basins that are cloud-free demonstrate a declining trend in snow cover from 2002 to 2024. Twelve of these basins exhibit a

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moderate negative correlation, meaning r is less than -0.30. The trend in snow cover from July to September also indicates a decline. Approximately 84% of the glacier basins show(n= a statistically significant negative correlation (P<0.05).

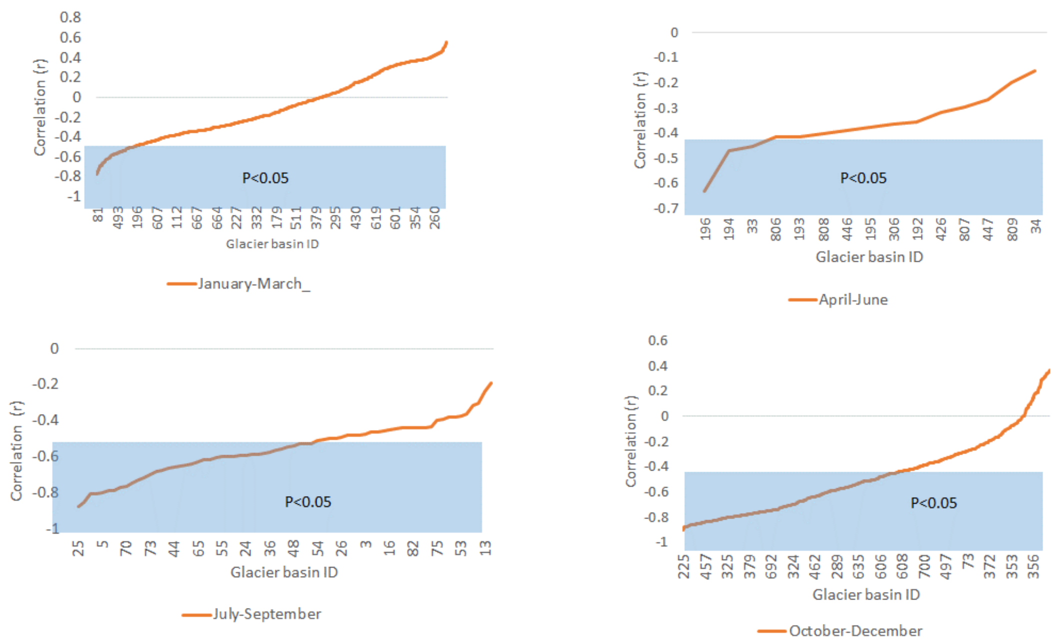

Figure 11. The correlation shows the snow cover change between 2002 and 2024 in different glacier basins.

The snow cover trend between July-September and October-December for 22 years also demonstrated a consistent decline in all glacier basins. Out of 604 basins selected for the analysis, about 60% have shown a statistically significant negative correlation (p<0.05), and although insignificant, 15 % of glacier basins showed a moderate negative correlation, i.e., r= -0.47 to -0.30 (Figure 10). The snow cover in the rest basins exhibits a poor negative correlation yet indicates a decline in snow cover over the period.

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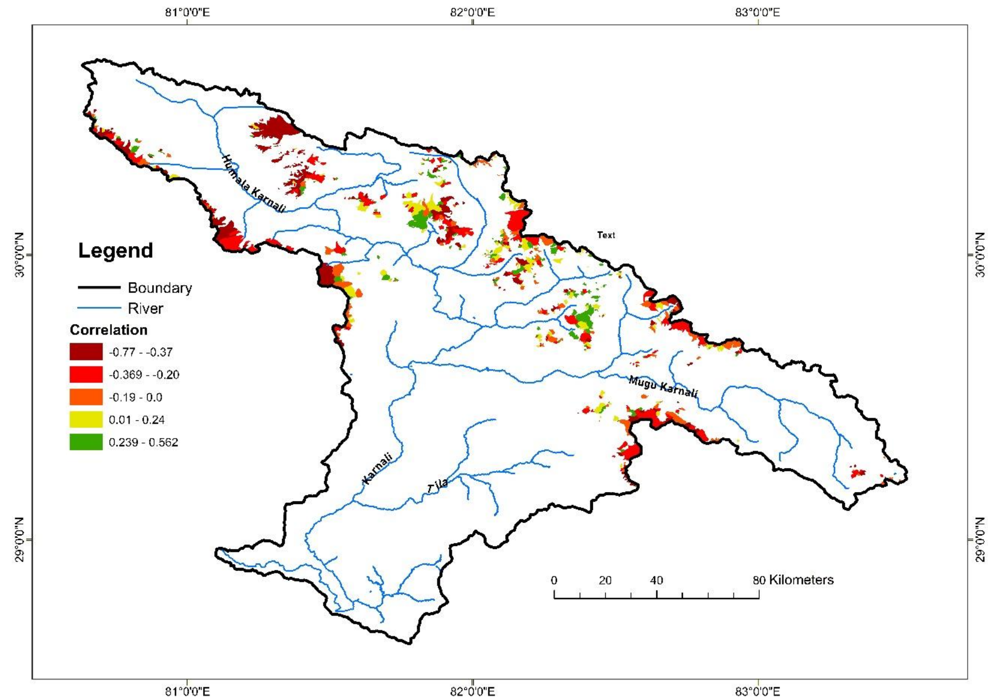

Figure 12. Snow cover trend on the Glacier Basins for January-March between 2000-2023 (Landsat 5, 7, and 8.

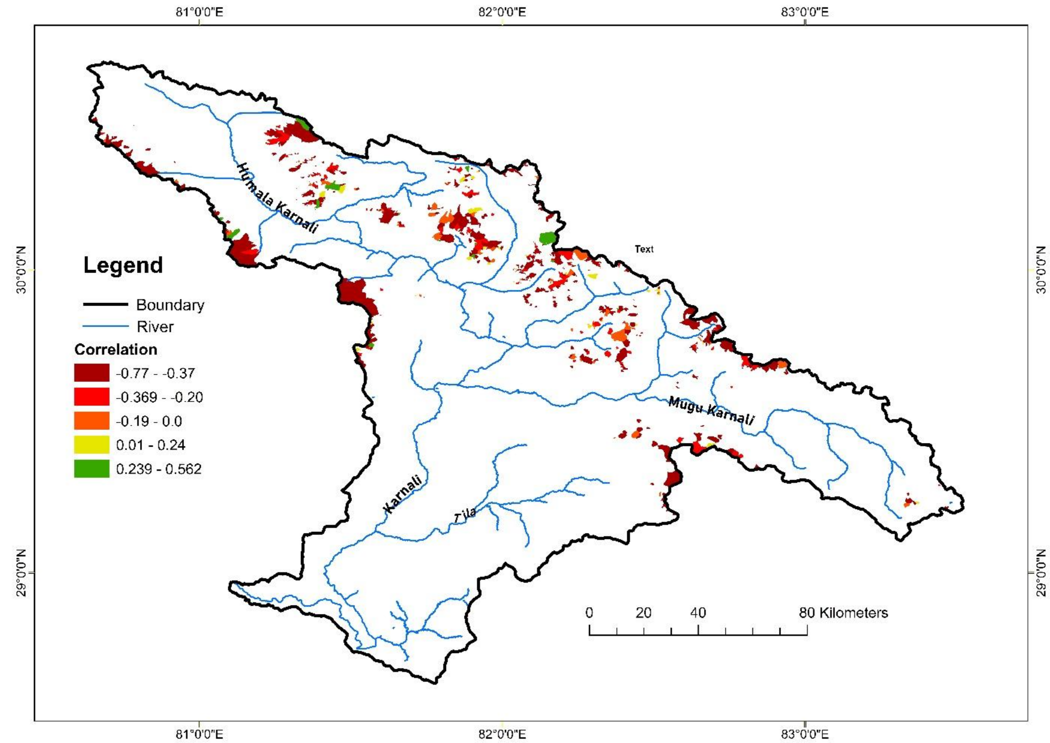

Figure 13. Snow cover trend on the glacier basins for October-December between 2000-2023 (Landsat 5, 7, and 8).

4.6. Snowline shift across elevations

The areas covered in snow were derived from the Landsat series 7, 8, and 9 by classifying snow using the Normalized Difference Snow Index (NDSI) algorithm to analyze changes in the snowline. This analysis was performed on the Google Earth Engine (GEE) platform. Snow pixels were identified with an NDSI threshold of > 0.4. The elevation-wise distribution of snow pixels was then calculated. To determine the minimum elevation of the snowline and its shift over the period from 2002 to 2024, three statistical thresholds were applied: the 10th, 25th, and 50th percentiles of the snow cover distribution across various elevations.

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The analysis of snowline altitude data from 2002 to 2024 reveals a significant upward trend across all percentiles (Figure 14). The 10th percentile shows the largest increase, with a Kendall’s tau of 0.2662 and a Sen’s slope of approximately 5.16 m/year, indicating that the lower snowline is rising quickly (Table 5). The 25th percentile presents a moderate yet statistically significant trend, with a Kendall’s tau of 0.1938 and a Sen’s slope of about 2.91 m/year. In contrast, the 50th percentile displays a gentler trend, with a Kendall’s tau of 0.1483 and a Sen’s slope of around 1.54 m/year, which remains statistically significant ($p<0.05$). Collectively, these findings suggest that the snowline is progressively moving to higher elevations, likely reflecting broader climatic changes that are affecting lower elevations more intensively than the median snowline altitude.

Table 5. Statistical Analysis of Snow Line Altitude Trends Using Kendall's Tau and Sen's Slope

Snow Line Percentile	Kendall's Tau	p-value	Sen's Slope (m/year)	Significance
10th Percentile (SLA_10P)	0.2662	0.00042	5.16	Significant (p < 0.001)
25th Percentile (SLA_25P)	0.1938	0.01022	2.91	Significant (p < 0.05)
50th Percentile (SLA_50P)	0.1483	0.04942	1.54	Significant (p < 0.05)

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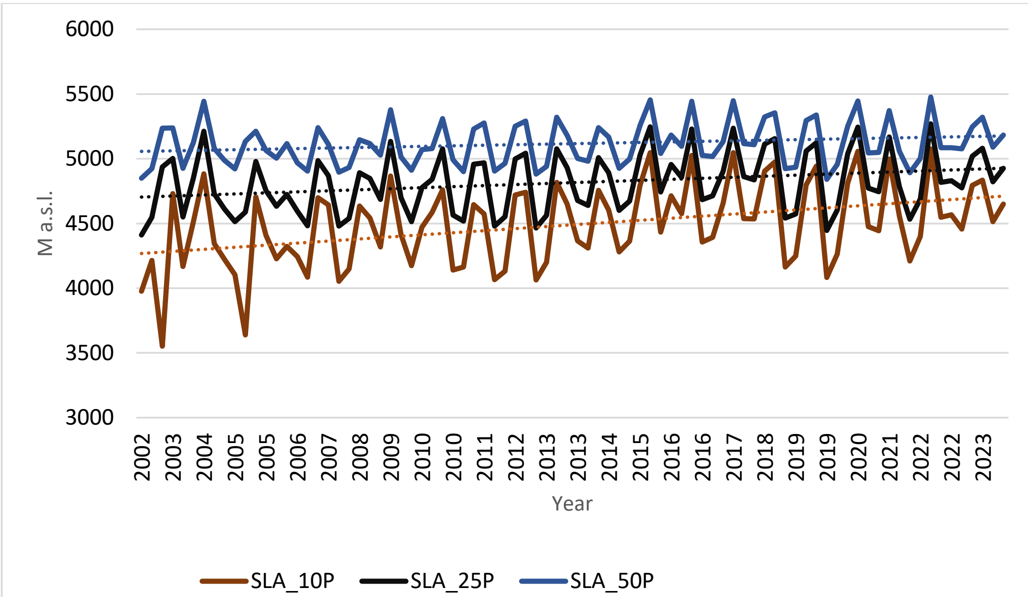

Figure 14. Snowline shift using snow line of elevation of 10, 25 and 50 percentile

5. Discussions

This study's findings offer important insights into the interactions between snow and ice cover in the Upper Karnali Basin (UKB) and climatic and topographic factors. The results reveal notable trends and fluctuations in snow cover, glacial retreat, and the elevation of the snowline, aligning with the wider patterns of climate change seen in the Himalayan region. We will discuss the key findings below in relation to existing literature and their impact on water resources, ecosystems, and local communities.

The study on the Upper Karnali Basin from 2002 to 2024 reveals significant insights into the relationship between snow cover area (SCA), temperature, and precipitation. The annual average SCA is 872 km², with the highest snow cover occurring from January to March (1528 ± 333 km²) and the lowest from July to September (212 ± 38.3 km²). The findings reveal a gradual decline in snow cover across the Upper Karnali Basin (UKB) from 2002 to 2024, with an average loss of ~3.99 km²/year.

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There is a strong to moderate negative correlation between snow cover and temperature across all seasons (r = -0.59 to -0.77, $p < 0.05$), signifying that higher temperatures lead to reduced snow cover. In contrast, precipitation exhibits a positive correlation with snow cover in winter (January to March and October to December), although this precipitation does not appear to facilitate snow accumulation. The reduction in snow cover during winter months (January-March) indicates a potential shift in precipitation patterns, with more falling as rain instead of snow, resulting in increased snowmelt, aligning with global warming trends (Wester et al., 2019). During the summer months (April to September), however, precipitation negatively correlates with snow cover, falling predominantly as rain, thus further enhancing snowmelt. Particularly, the period from July to September reveals a statistically significant decrease in snow cover (Sen's Slope = -2.87, $p<0.05$), primarily driven by warmer temperatures and higher rainfall during the summer monsoon, accelerating snowmelt.

The interannual variability in snow cover highlights the sensitivity of snowpack to fluctuating temperature and precipitation regimes. This variability has significant implications for water availability, as snowmelt is a critical source of freshwater for downstream communities, agriculture, and hydropower generation (Immerzeel et al., 2020). The observed decline in snow cover could exacerbate water scarcity during the dry season, affecting millions of people who rely on snowmelt for irrigation and drinking water (Pritchard, 2019).

Examining snow cover patterns in the UKB sub-basins reveals notable seasonal and spatial differences. The Humla Karnali sub-basin has the largest average snow cover during January-March, while downstream areas like Tila and Kawari exhibits

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(Pritchard, 2019). The strong negative correlation in Downstream Karnali ($r = -0.47$, $p < 0.05$) further highlights the declining trend in snow cover, which could disrupt water availability and ecosystem services in the region (Wester et al., 2019).

The findings emphasize the vulnerability of the UKB to climate change, with rising temperatures and shifting precipitation patterns leading to reduced snow cover. Adaptive water management strategies are essential to mitigate the impacts on water resources and local communities.

The findings on snow cover dynamics across elevation zones in the Upper Karnali Basin reveal significant elevation-dependent patterns, driven by temperature fluctuations and global warming. At lower elevations (≤2000 m a.s.l.), snow cover exhibits a weak positive correlation (0.12-0.43), suggesting a marginal increase, likely due to localized precipitation variability. However, this is accompanied by high interannual variability (CoV ~ 41-43%), indicating sensitivity to fluctuating temperature and precipitation regimes (Pepin et al., 2015). This variability underscores the vulnerability of lower elevations to climate change, where even minor temperature increases can significantly impact snow accumulation and melt.

The transition from weak negative correlations above 2300 m above sea level (m a.s.l.) to the strongest negative correlation at 6100-6200 m a.s.l. ($r = -0.56$) corresponds with comprehensive evidence of elevation-dependent warming (EDW) identified in recent studies. It has been globally observed that higher altitudes experience accelerated warming, leading to reduced snow accumulation and increased melt rates (Elevation-dependent warming in mountain regions of the world, 2015; Krishnan et al., 2019; Pepin et al., 2022; Shen et al., 2021; Naegeli et al., 2019) The sharp rise in mean snow cover above 5000 m a.s.l. coincides with permanent snow and glacier zones, but the decline in inter-annual variability (CoV) suggests a consistent reduction in snow cover, particularly at mid-to-high elevations (3000–5000 m a.s.l.).

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The nonlinear relationship between elevation and snow cover variability (CoV) proves particularly insightful. Below 3100 m a.s.l., CoV reaches 41–43%, reflecting transitional zones where slight temperature fluctuations determine precipitation phase (rain vs. snow). Above 3,100 m a.s.l., CoV drops to 25–30% as conditions remain persistently below freezing, but the dominant driver shifts to insolation and temperature-modulated melt rates. This aligns with Ren et al.'s (2023) findings on Tibetan Plateau glaciers, where albedo feedbacks dominate mass balance above 5000 m a.s.l.

The strong negative correlation between land surface temperature and snow cover (Tau = -0.43 to -0.79) further highlights the impact of rising temperatures on snowpack. The most severe declines occur between 3000-5000 m a.s.l., where warming accelerates snowmelt and glacier retreat, threatening water availability for river flows, agriculture, and hydropower (Immerzeel et al., 2020). This elevation-dependent warming exacerbates glacier mass loss, leading to a negative mass balance and reduced freshwater storage, which has profound implications for downstream communities reliant on meltwater (Bolch et al., 2012).

Snow cover trends in glacier basins within the Upper Karnali Basin reveals significant declines in both glacier area and snow cover from 2000 to 2023. The mean glacier area decreased from 119.046 hectares in 2000 to 100.472 hectares in 2023, reflecting an average loss of 18.574 hectares per basin. This widespread glacier retreat is consistent across all basin orientations, with the most significant losses observed in north-facing basins (N, NW, NE), totaling -6,126.9 hectares. The reduction in glacier area is attributed to rising temperatures and decreased snowfall, which disrupt the glacier mass balance, leading to accelerated melting and negative mass balance (Pepin et al., 2022; Ye and Tian, 2022; Pei Ren et al., 2024). The decline in permanent snow cover further exacerbates these effects, threatening glacier persistence and altering water availability.

Snow cover trends in glacier basins also show a consistent decline, particularly during winter (January-March) and post-monsoon (October- December) seasons. Approximately 63% of glacier basins exhibit negative correlations in snow cover from January to March, with 16.3% showing statistically significant

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declines ($r < -0.44$, $p < 0.05$). Similarly, 84% of glacier basins demonstrate significant negative correlations in snow cover from July to September, indicating a substantial seasonal decline. The reduction in snow cover is linked to rising temperatures, which increase snowmelt rates and reduce albedo, further accelerating glacier retreat (Dowson et al., 2020). These trends highlight the vulnerability of glacier basins to climate change, with significant implications for water security and regional hydrology.

One of the most alarming findings is the steady upward migration of the snowline, as revealed by the snow elevation percentile analysis. The 10th percentile snowline has shifted upward by ~5.6 meters per year, while the 25th and 50th percentiles show a more moderate but significant rise (~2.91 and 1.54 meters per year, respectively). This indicates a systematic retreat of seasonal snow cover to higher elevations, reducing the snow accumulation potential for glacier mass balance maintenance.

Feedback mechanisms and future projections

The temperature–snow cover correlation (τ = -0.43 to -0.79 across elevations) establishes a reinforcing feedback loop: 1. Warming reduces snow cover, lowering surface albedo, 2. Absorbed solar radiation increases local temperatures by 0.8-1.2°C (estimated from Sen's slope), and enhanced melting further reduces albedo, accelerating the cycle.

At current warming rates (0.0643°C/year above 5,000 m a.s.l.), the UKB could lose 70–80% of its glacier area by 2050, reflecting Ye and Tian's (2022) projections for the central Himalayas. This would transform the basin's hydrology from nival (snowmelt-dominated) to pluvial (rain-dominated), increasing flood risks during monsoons and drought susceptibility in dry seasons.

The findings highlight the continuing effects of climate change on glacier-fed regions. Increasing temperatures and changing precipitation patterns are causing reductions in glacier area and snow cover, which has significant implications for water resources, ecosystems, and local communities dependent on glacier meltwater.

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Conclusions

The study of snow and glacier cover dynamics in the Upper Karnali Basin from 2002 to 2024 reveals a persistent decline in snow cover, glacier area, and snowline elevation, driven by rising temperatures and altered precipitation patterns.

The annual snow-covered area (SCA) has decreased by approximately 3.99 km² per year, with the most significant reductions observed during the July-September monsoon period. The decline in snow cover is statistically correlated with increasing temperatures, demonstrating the impact of climate change on seasonal snow accumulation and melt cycles. The winter snow cover variability suggests changes in snowfall patterns rather than a uniform decrease.

Notable seasonal and spatial differences in snow cover patterns are observed in the Sub-basins of UKB for two seasons, January-March and October-December. The upstream sub-basins experience less inconsistent snowfall than the downstream basins. During October-December, snowfall is inconsistent in all basins, but more inconsistent in particularly China Karnali, Tila and Downstream Karnali.

Elevation-dependent trend analysis confirms that snow cover at lower elevations (<2000 m a.s.l.) exhibits high interannual variability, while higher elevations (>3000 m a.s.l.) show a significant long-term decline. The strongest reductions occur between 3000–5000 m a.s.l., where warming accelerates snowmelt and glacier retreat. The observed negative correlation between snow cover and rising temperatures confirms the climate-driven reduction in snowpack, exacerbating the risk of water shortages.

The study of glacier basins shows widespread retreat, with the mean glacier area declining from 119.046 hectares in 2000 to 100.472 hectares in 2023. Glacier retreat is most pronounced in north-facing basins (N, NW, NE), where melting exceeds accumulation. The continuous decline in snow cover across glacier basins indicates an ongoing negative mass balance, threatening long-term glacier persistence.

Additionally, the snow line is gradually shifting upward, with the 10th, 25th, and 50th percentiles rising by approximately 5.16, 2.91, and 1.54 meters per year, respectively, indicating a consistent loss of seasonal snow accumulation.

Given the current warming trends (~0.0643°C/year above 5000 m a.s.l.), the UKB could experience a 70-80% reduction in glacier area by 2050. This would transform the hydrology from snowmelt-dominated (nival) to rainfall-dominated (pluvial), increasing the frequency of extreme weather events and altering regional water security dynamics. The findings emphasize the need for proactive water resource management, improved climate resilience strategies, and continuous monitoring of cryospheric changes to mitigate future risks. Policymakers must prioritize adaptation measures, such as improved water storage infrastructure and sustainable land-use practices, to ensure long-term water security in the Upper Karnali Basin and beyond.

Author contributions

MG conceptualized the research, designed the methodology, conducted fieldwork, analyzed the data, and drafted the manuscript. DS. and RC assisted in proposal writing, research design, fieldwork, and data analysis. AT, TPPS, KPS, SBG, and SD contributed to procuring remote sensing and climate data. PB and SK were responsible for procuring and updating MODIS data. WY reviewed the manuscript and provided feedback to enhance its quality. NT and JK assisted in GIS analysis. All authors contributed to revising the manuscript and provided input before submission.

Competing Interests

The authors declare that they have no conflict of interest.

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References

Anup, K. (2017). Climate change and its impact on tourism in Nepal. *Journal of Tourism and Hospitality Education*, 7, 25-43.

Bajracharya, S. R., Bajracharya, O. R., Baidya, S., Maharjan, S. B., & Shrestha, F. 2014 (2014) 'Climate change impact on glaciers in the Langtang and Imja sub-basins of Nepal from late 70s to 2010' *AGU Fall Meeting Abstracts*. pp. C31B-0278.

Bajracharya, S. R., Mool, P. K., & Shrestha, B. R. (2008). Global climate change and melting of Himalayan glaciers. *Melting glaciers and rising sea levels: Impacts and implications*, 28-46.

https://doi.org/10.5194/egusphere-2025-1303
Preprint. Discussion started: 8 May 2025

Bishop, M. P., Olsenholler, J. A., Shroder, J. F., Barry, R. G., Raup, B. H., Bush, A. B., et al. (2004). Global Land Ice Measurements from Space (GLIMS): remote sensing and GIS investigations of the Earth's cryosphere. *Geocarto International*, 19(2), 57-84.

Bolch, T. (2007). Climate change and glacier retreat in northern Tien Shan (Kazakhstan/Kyrgyzstan) using remote sensing data. *Global and Planetary Change*, 56(1-2), 1-12.

Bolch, T., Kulkarni, A., Kääb, A., Huggel, C., Paul, F., Cogley, J. G., et al. (2012). The state and fate of Himalayan glaciers. *Science*, 336(6079), 310-314.

Bookhagen, B., & Burbank, D. W. (2010). Toward a complete Himalayan hydrological budget: Spatiotemporal distribution of snowmelt and rainfall and their impact on river discharge. *Journal of Geophysical Research: Earth Surface*, 115(F3).

Dowson, A. J., Sirguey, P., & Cullen, N. J. (2020). Variability in glacier albedo and links to annual mass balance for the gardens of Eden and Allah, Southern Alps, New Zealand. *The Cryosphere*, 14(10), 3425-3448.

Elevation-dependent warming in mountain regions of the world (2015). *Nature climate change*, 5(5), 424-430.

Elsasser, H., & Bürki, R. (2002). Climate change as a threat to tourism in the Alps. *Climate research*, 20(3), 253-257.

Forster, P., Storelvmo, T., & Alterskjæ, K. (2021) 'IPCC sixth assessment report (AR6) working group 1: the physical science basis, chap. 7'. University Press, UK, https://www. ipcc. ch/report/ar6/wg1/downloads (last ….

Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., & Moore, R. (2017). Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote sensing of Environment*, 202, 18-27.

https://doi.org/10.5194/egusphere-2025-1303
Preprint. Discussion started: 8 May 2025

Gurung, D. R., Maharjan, S. B., Shrestha, A. B., Shrestha, M. S., Bajracharya, S. R., & Murthy, M. (2017). Climate and topographic controls on snow cover dynamics in the Hindu Kush Himalaya. *Int. J. Climatol*, 37(10), 3873-3882.

Hall, D. K., Riggs, G. A., Salomonson, V. V., DiGirolamo, N. E., & Bayr, K. J. (2002). MODIS snow-cover products. *Remote sensing of Environment*, 83(1-2), 181-194.

Heid, T., & Kääb, A. (2012). Repeat optical satellite images reveal widespread and long term decrease in land-terminating glacier speeds. *The Cryosphere*, 6(2), 467-478.

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al. (2020). The ERA5 global reanalysis. *Quarterly journal of the royal meteorological society*, 146(730), 1999-2049.

Immerzeel, W. W., Lutz, A. F., Andrade, M., Bahl, A., Biemans, H., Bolch, T., et al. (2020). Importance and vulnerability of the world's water towers. *Nature*, 577(7790), 364-369.

Kääb, A., Berthier, E., Nuth, C., Gardelle, J., & Arnaud, Y. (2012). Contrasting patterns of early twenty-first-century glacier mass change in the Himalayas. *Nature*, 488(7412), 495-498.

Kääb, A., Huggel, C., Fischer, L., Guex, S., Paul, F., Roer, I., et al. (2005). Remote sensing of glacier-and permafrost-related hazards in high mountains: an overview. *Natural Hazards and Earth System Sciences*, 5(4), 527-554.

Krishnan, R., Shrestha, A. B., Ren, G., Rajbhandari, R., Saeed, S., Sanjay, J., et al. (2019). Unravelling climate change in the Hindu Kush Himalaya: rapid warming in the mountains and increasing extremes. *The Hindu Kush Himalaya assessment: Mountains, climate change, sustainability and people*, 57-97.

Kulkarni, A. V., Shirsat, T. S., Kulkarni, A., Negi, H., Bahuguna, I., & Thamban, M. (2021). State of Himalayan cryosphere and implications for water security. *Water Security*, 14, 100101.

Mimura, N. (2013). Sea-level rise caused by climate change and its implications for society. *Proceedings of the Japan Academy, Series B*, 89(7), 281-301.

Mishra, B., Babel, M. S., & Tripathi, N. K. (2014). Analysis of climatic variability and snow cover in the Kaligandaki River Basin, Himalaya, Nepal. *Theoretical and applied climatology*, 116, 681-694.

Mool, P. K., Bajracharya, S. R., & Joshi, S. P. (2001). Inventory of glaciers, glacial lakes and glacial lake outburst floods. Monitoring and early warning systems in the Hindu Kush-Himalayan Region: Nepal.

Muhammad, S., & Thapa, A. (2020). An improved Terra–Aqua MODIS snow cover and Randolph Glacier Inventory 6.0 combined product (MOYDGL06*) for high-mountain Asia between 2002 and 2018. *Earth System Science Data*, 12(1), 345-356.

Naegeli, K., Huss, M., & Hoelzle, M. (2019). Change detection of bare-ice albedo in the Swiss Alps. *The Cryosphere*, 13(1), 397-412.

NOAA (2013). Sea Levels Online. . NOAA. https://tidesandcurrents.noaa.gov/sltrends/sltrends.html. Accessed.

Nyaupane, G. P., & Chhetri, N. (2009). Vulnerability to climate change of nature-based tourism in the Nepalese Himalayas. *Tourism Geographies*, 11(1), 95-119.

Pendergrass, A. G. (2020). Changing degree of convective organization as a mechanism for dynamic changes in extreme precipitation. *Current Climate Change Reports*, 6, 47-54.

Pepin, N. C., Arnone, E., Gobiet, A., Haslinger, K., Kotlarski, S., Notarnicola, C., et al. (2022). Climate changes and their elevational patterns in the mountains of the world. *Reviews of geophysics*, 60(1), e2020RG000730.

Pfeffer, W. T., Arendt, A. A., Bliss, A., Bolch, T., Cogley, J. G., Gardner, A. S., et al. (2014). The Randolph Glacier Inventory: a globally complete inventory of glaciers. *Journal of glaciology*, 60(221), 537-552.

https://doi.org/10.5194/egusphere-2025-1303
Preprint. Discussion started: 8 May 2025

Pritchard, H. D. (2019). Asia's shrinking glaciers protect large populations from drought stress. *Nature*, 569(7758), 649-654.

Ren, P., Pan, X., Liu, T., Huang, Y., Chen, X., Wang, X., et al. (2024). Glacier changes from 1990 to 2022 in the Aksu River Basin, western Tien Shan. *Remote Sensing*, 16(10), 1751.

Ren, S., Jia, L., Menenti, M., & Zhang, J. (2023). Changes in glacier albedo and the driving factors in the Western Nyainqentanglha Mountains from 2001 to 2020. *Journal of Glaciology*, 69(277), 1500-1514.

Shen, L., Zhang, Y., Ullah, S., Pepin, N., & Ma, Q. (2021). Changes in snow depth under elevation-dependent warming over the Tibetan Plateau. *Atmospheric Science Letters*, 22(9), e1041.

Shrestha, A. B., & Aryal, R. (2011). Climate change in Nepal and its impact on Himalayan glaciers. *Regional environmental change*, 11, 65-77.

Shrestha, M., Wang, L., Koike, T., Xue, Y., & Hirabayashi, Y. (2012). Modeling the spatial distribution of snow cover in the Dudhkoshi region of the Nepal Himalayas. *Journal of Hydrometeorology*, 13(1), 204-222.

Wester, P., Mishra, A., Mukherji, A., & Shrestha, A. B. (2019). The Hindu Kush Himalaya assessment: mountains, climate change, sustainability and people. Springer Nature.

Xu, J., Grumbine, R. E., Shrestha, A., Eriksson, M., Yang, X., Wang, Y., et al. (2009). The melting Himalayas: cascading effects of climate change on water, biodiversity, and livelihoods. *Conservation Biology*, 23(3), 520-530.

Ye, Y., & Tian, Y. (2022). Interpreting changes in albedo and mass balance at White Glacier, Canadian Arctic Archipelago. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 43, 793-798.

https://doi.org/10.5194/egusphere-2025-1303
Preprint. Discussion started: 8 May 2025

Zemp, M. (2006) Glaciers and climate change: spatio-temporal analysis of glacier fluctuations in the European Alps after 1850. University of Zurich

NASA LP DAAC. (2023). *MODIS/Aqua Land Surface Temperature and Emissivity 8-Day L3 Global 1 km SIN Grid, Version 6.1* [Data set]. NASA Land Processes Distributed Active Archive Center (LP DAAC). Accessed via AppEEARS on 2025-02-15. Available at: https://doi.org/10.5067/MODIS/MYD11A2.061

ECMWF. (2023). *ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global climate*. Copernicus Climate Change Service (C3S). Retrieved from https://cds.climate.copernicus.eu/