

## Integrated Analysis of Climate Change Effects on Cryospheric and Hydrological Processes in the Dudhkoshi Basin

Reshu Karki<sup>1,2</sup>, Dhiraj Pradhananga<sup>1,2</sup>, Kumar Aryal<sup>1,2\*</sup>, Insaf Aryal<sup>3</sup>, Aakriti Dhakal<sup>1</sup>, Susa Manandhar<sup>1</sup>, Tribikram Basnet<sup>1</sup>, Subhekshya Pandey<sup>1</sup>, Ashok Ghimire<sup>1</sup>, Sushant Dhital<sup>1</sup>

<sup>1</sup>The Small Earth Nepal (SEN), Kathmandu, Nepal

<sup>2</sup>Department of Meteorology, Tri-Chandra Multiple Campus, Kathmandu, Nepal

<sup>3</sup>Institute of Engineering (IoE), Tribhuvan University, Lalitpur, Nepal

\*Corresponding author: Kumar Aryal, [kumar.aryal@smallearth.org.np](mailto:kumar.aryal@smallearth.org.np)

### Abstract

The Himalayan region is highly sensitive to climate change, where rising temperatures and changing precipitation patterns are directly influencing cryospheric processes and downstream hydrology. This study investigates long-term climatic and cryospheric variations in the Dudhkoshi Basin. We used ERA5 reanalysis data for temperature and precipitation (1995 to 2024), MODIS snow cover (2000 - 2024), and GloFAS discharge data (1995 - 2023) to analyse trends and relationships. Sen's slope estimator and Mann-Kendall test were used to examine trends, while correlation analysis assessed the relationships between discharge, snow cover, and climate drivers. The results indicate a significant warming trend of +0.04 °C/year and an increasing trend in precipitation of +16 mm/year. Discharge also shows a notable increasing trend of +1.5 m<sup>3</sup>/s/year, reflecting intensifying hydrological conditions. Although not statistically significant, a declining trend in snow cover with extensive seasonal fluctuation is also observed. Correlation analysis highlights a strong negative relationship between temperature and snow cover ( $r = -0.46$ ,  $p < 0.05$ ), while precipitation has a seasonally varying influence, showing a strong positive correlation during winter. These findings emphasize the cryosphere of the basin's sensitivity to climate change and the influence of temperature and precipitation on snow cover dynamics and water yield.

**Keywords:** Climate change, Dudhkoshi basin, Cryosphere, Snow cover, Remote sensing

### 1. Introduction

Mountains are often referred to as the “water towers of the world”, providing freshwater to billions of people living downstream (Viviroli et al., 2007). Among them, the Hindu Kush Himalayan (HKH) region, also known as the “Third Pole”, contains the largest reserve of ice and snow outside the polar regions. This region plays a vital role in maintaining the hydrology of South and Central Asia (Bolch et al., 2012). However, this region is warming faster than the global average. Projections indicate that temperatures in the HKH could increase by 2.6 - 4.6 °C by the end of the 21st century under moderate emission scenarios (Krishnan et al., 2020). In Nepal, observed trends reveal rising temperatures averaging around 0.06 °C per year, with faster rates at higher elevations. Precipitation patterns also show strong spatial variability: while western Nepal receives less than 2000 mm of annual rainfall, central and eastern regions may exceed 5000 mm (Ichiyanagi et al., 2007).

Rising temperatures are impacting key components of the hydrological cycle by altering the precipitation patterns, reducing snow cover, and accelerating glacier melt (Panthi et al., 2015). These shifts are intensifying precipitation extremes, heightening flood risks, and amplifying the variability in river discharge (Pokharel et al., 2020a; Subba et al., 2019). Accelerated snow and ice loss has further contributed to the expansion of glacial lakes, increasing the risk of glacial lake outburst floods (GLOFs) (Ahmed et al., 2021). These changes have significant impacts on water availability, river discharge, and the livelihoods of communities downstream, particularly in countries like Nepal, where complex topography leads to substantial spatial and temporal variability in

precipitation and temperature (Pokharel et al., 2020a; Talchabhadel et al., 2022, Sapkota et al., 2025). Tracking the extent and patterns of snow cover in the high-altitude Trans-Himalayan Region (THR) has become crucial for understanding the local as well as regional impacts of ongoing climate change and variability (Paudel & Andersen, 2011).

Despite their importance, mountain systems remain underrepresented in large-scale climate studies due to a sparse in-situ data network in rugged terrains (Panthi et al., 2015). Recent advancements in reanalysis products and remote sensing datasets have enhanced the ability to detect climate trends and assess their hydrological impacts in data-scarce regions (Bell et al., 2021; Deng et al., 2024).

Although many studies have examined individual aspects of climate change in the Himalayas, such as snow cover dynamics, precipitation variability, or changes in river discharge, comprehensive assessments integrating these variables are still limited (Khadka et al., 2016; Nepal, 2016a). Major uncertainties persist, particularly in contributions of snow, rainfall, and glacier melt to streamflow in the HKH region (Armstrong et al., 2019a; Wulf et al., 2016). Addressing the gap of integrating cryosphere and hydrology remains uncertain, even though essential for understanding how climate change affects this interconnected system.

Therefore, this study focuses on addressing the gap in the correlation of cryospheric parameters to hydrology for the Dudhkoshi Basin in eastern Nepal, one of the country's most glacierized catchments and a critical source of water for downstream communities and hydropower development (Bajracharya & Mool, 2009). By analysing long-term climate and

hydrological datasets, this research aims to (i) assess observed trends in temperature, precipitation, and snow cover, (ii) evaluate their impact on streamflow, and (iii) explore the implications for future water availability and potential hazards. By integrating cryospheric and hydrological perspectives, this research contributes to a holistic understanding of climate change impacts in the Himalayan basin and provides insight for sustainable water management for highly snow and glacier-dominated catchments.

## 2. Data and Methods

### 2.1. Study area

The Dudhkoshi Basin (Figure 1), situated in eastern Nepal, between latitude 27°16'-28°30'N and longitude

86°30'-87°06'E (Pokhrel et al., 2014) is characterized by its steep gradients, shapes, and both dynamic and hydrological processes (Savéan et al., 2015). Due to wide elevation change, the basin experiences diverse climates with temperate climates in the lower altitudes and sub-alpine climates in higher elevations. The region's climate is characterized by four distinct seasons: cold and dry winter with minimal precipitation (December to February), hot and humid summer (June to September), which delivers 82% of annual precipitation and approximately 77% of total discharge, and two transitional periods: pre-monsoon (March, April, and May) and post-monsoon (October and November) (Mimeau et al., 2019; Nepal et al., 2015)

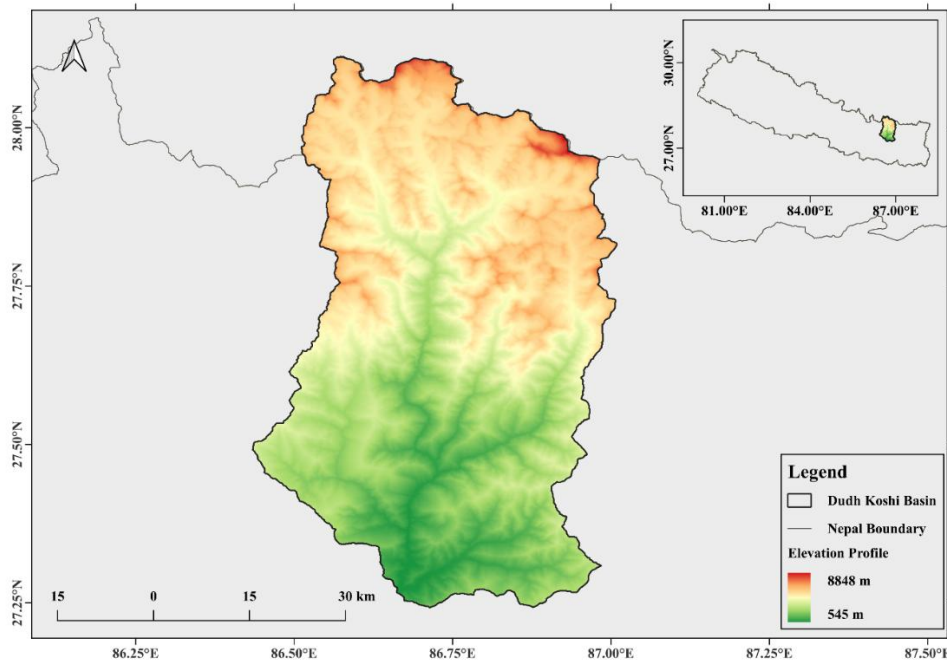


Figure 1: Dudhkoshi Basin

### 2.2. Data used

The MODIS snow cover data with a spatial resolution of 500m was utilized (Table 1). The satellite covers the entire Earth every one to two days and provides images with resolutions of 250 m, 500 m, and 1000 m. The snow cover data were correlated with the ERA5 temperature and precipitation data, which have a spatial resolution of approximately 28 km (0.25°).

A NASA DEM with a spatial resolution of 30 m was used to calculate the snowline. To align the coarser resolution MODIS data, the DEM was resampled accordingly. The discharge data were obtained from the Global Flood Awareness System (GloFAS), which comprises a collection of forecasted time series data arranged on a global grid.

### 2.3. Methods

The hourly ERA5 temperature and precipitation data of 0.25° x 0.25° resolution were downloaded from Copernicus Climate Data Store and aggregated to daily, seasonal, and annual timescales. Discharge data taken from GloFAS were resampled to annual and seasonal means to align with climate and snow measurements.

Table 1: Details of data used

Data	Date	Resolution	Source
Snow cover	2000 to 2024	0.005°	<a href="https://modis.gsfc.nasa.gov/data/">https://modis.gsfc.nasa.gov/data/</a>
Temperature	1995 to 2024	0.25°	<a href="https://cds.climate.copernicus.eu/">https://cds.climate.copernicus.eu/</a>
Precipitation	1995 to 2024	0.25°	<a href="https://cds.climate.copernicus.eu/">https://cds.climate.copernicus.eu/</a>
Discharge	1995 to 2023	0.05°	<a href="https://ewds.climate.copernicus.eu/datasets/cems-glofas-forecast?tab=overview">https://ewds.climate.copernicus.eu/datasets/cems-glofas-forecast?tab=overview</a>

The fraction of each pixel covered by snow was represented by converting MODIS daily snow cover values (0-100%) from the year 2000 (Hall & Riggs, 2021). Fractional snow cover was converted to snow-covered area (km<sup>2</sup>) for each pixel. The total snow cover area was then calculated by summing all the relevant pixels, which was then used to construct the time series of total snow cover area. The Digital Elevation Model (DEM) from NASA's global DEM initially of 30 m resolution was also resampled to 500 m resolution to

ensure snow cover and elevation were spatially aligned with the MODIS snow cover data. The annual snowline was extracted from MODIS snow cover and DEM data using a weighted mean elevation approach. A threshold snow fraction value of 0.2 (20%) was applied to eliminate the pixels influenced by clouds or areas having little snow coverage (Zhang et al., 2010). Snow fraction was used as a weighting variable to calculate the weighted annual average elevation, where pixels with more snow were prioritized.

Correlation analysis was performed at annual and seasonal timescales to evaluate the pairwise association

between variables. Pearson's correlation coefficients were computed between temperature and snow cover, precipitation and snow cover, temperature and discharge, precipitation and discharge, snow elevation and temperature, and other relevant pairs. Statistical significance was tested at a 95% confidence level ( $p < 0.05$ ), which scaled from -1 to +1 (Schober et al., 2018). To study the combined effects, multiple correlation analysis was conducted, and it analyses how temperature, precipitation, and snow cover together account for changes in discharge. The detailed workflow of the methodology is presented in Figure 2.

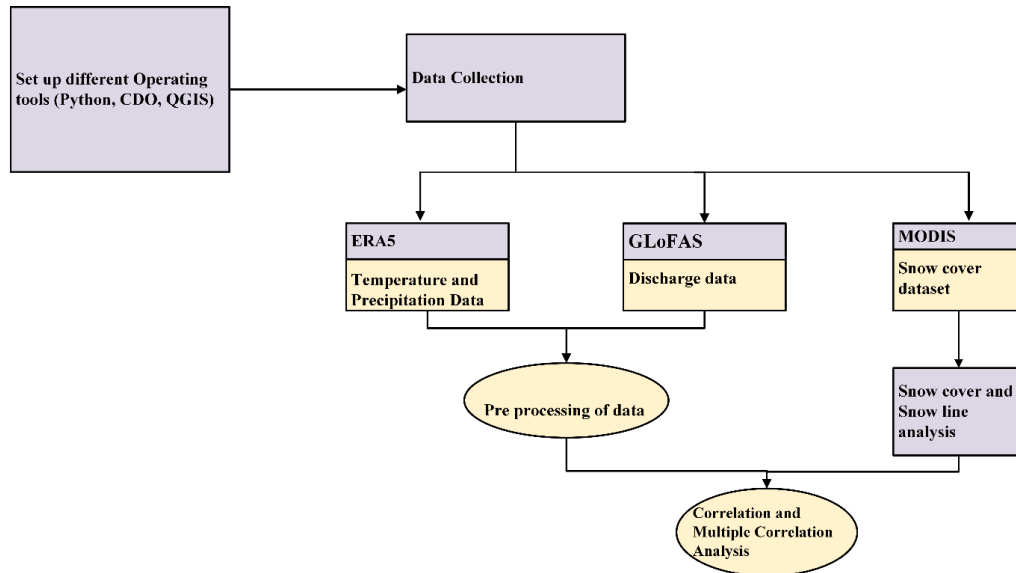


Figure 2: Methodological Chart

#### 2.4. Analysis tools

For analysing the datasets, a variety of geospatial tools, command-line applications, and programming languages, including Quantum GIS (QGIS), Climate Data Operators (CDO), and Python, were employed. These tools provided a user-friendly, robust, and comprehensive environment for working with climate-related datasets (Kaspar et al., 2010; Khan & Mohiuddin, 2018; Stancin & Jovic, 2019).

#### 2.5. Trend analysis

Trends in temperature, precipitation, snow cover, and snowline elevation were analysed in both annual and seasonal time scales. Seasonal analysis is based on hydrological seasons. In the context of Nepal, the hydrological seasons were classified into four categories: winter (December to February), pre-monsoon (March to May), monsoon (June to September), and post-monsoon (October and November). The rate of change for each variable was quantified using Sen's slope estimator, and the monotonic trend statistical significance was assessed using Mann-Kendall trend tests (Atta-ur-Rahman & Dawood, 2017; Gu et al., 2016; Volodin & Yurova, 2013). A 95% confidence level was determined to compute uncertainty, and linear regression trend lines were calculated for comparison.

### 3.0 Results and Discussion

#### 3.1 Temperature trends

The long-term and seasonal temperature trend from 1995 to 2024 of Dudhkoshi basin is shown in Figure 3 and 4; all four seasons exhibit positive slopes, indicating overall warming. Post-monsoon (Sen's slope =  $+0.049^{\circ}\text{C}/\text{year}$ ,  $p\text{-value} = 0.017$ ) and monsoon (Sen's slope =  $+0.037^{\circ}\text{C}/\text{year}$ ,  $p\text{-value} \ll 0.05$ ) have statistically significant increasing trends, indicating a rise in mean seasonal temperatures. On the other hand, winter (Sen's slope =  $+0.043^{\circ}\text{C}/\text{year}$ ,  $p\text{-value} = 0.285$ ) and pre-monsoon (Sen's slope =  $+0.016^{\circ}\text{C}/\text{year}$ ,  $p\text{-value} = 0.392$ ) exhibit non-significant warming trends, indicating high interannual variability.

#### 3.2 Precipitation trends

Figure 5 (the annual precipitation trend from 1995 to 2024) shows a statistically significant upward trend, as seen from Sen's slope of  $+16.04 \text{ mm}/\text{year}$  and a  $p\text{-value}$  of 0.002, which is a test of significance of the trend at the 95% confidence interval. The linear trend clearly shows an increase in precipitation over 30 years. Despite high interannual variability, including dry years such as 1997 and 2005 and wet years like 2011 and 2020, the general trend reflected a steady increase in annual precipitation. The trend suggests an intensification of the hydrological cycle in the region, possibly connected with regional climate change.

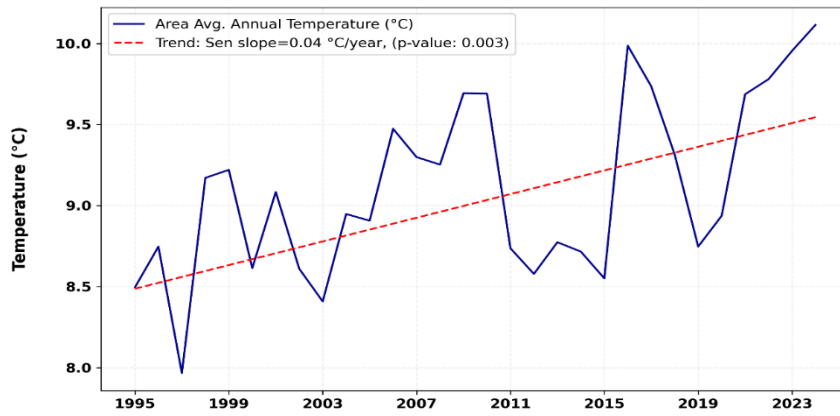


Figure 3: Temperature trend of Dudhkoshi River basin from 1995 to 2024

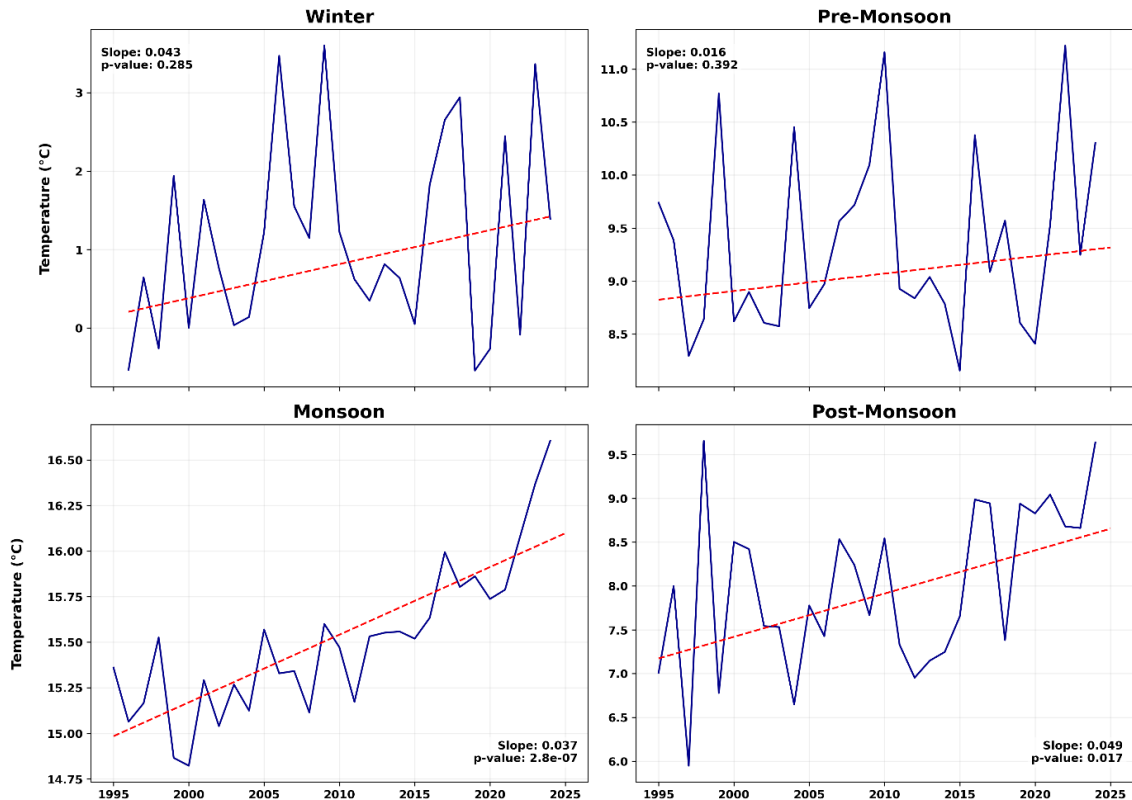


Figure 4: Seasonal temperature trend from 1995 to 2024

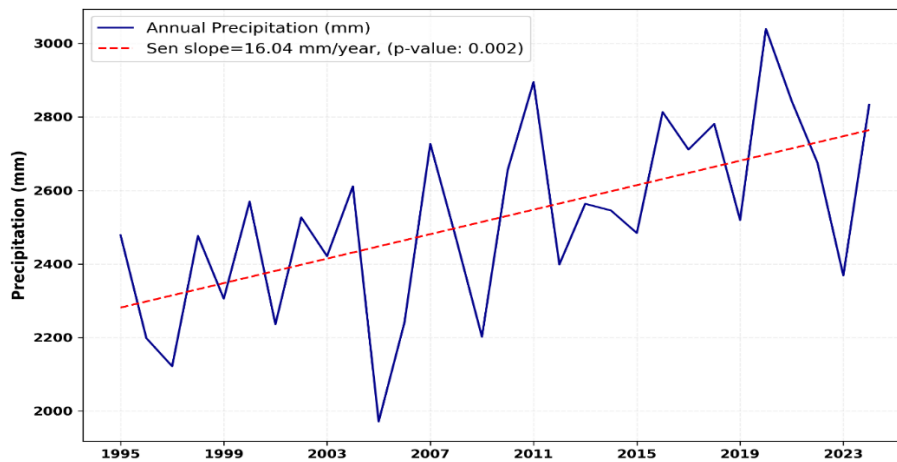


Figure 5: Annual precipitation trend from 1995 to 2024

Seasonal precipitation trends in Figure 6 show an upward trend for precipitation during the pre-monsoon, but not significant (Sen's slope = 2.22, p-value = 0.118). However, the increase in trend during the monsoon

period is significant (Sen's slope = 16.249, p-value = 0.001). On the other hand, winter and post-monsoon precipitation follow a declining trend, although it is not statistically significant ( $p > 0.05$ ).

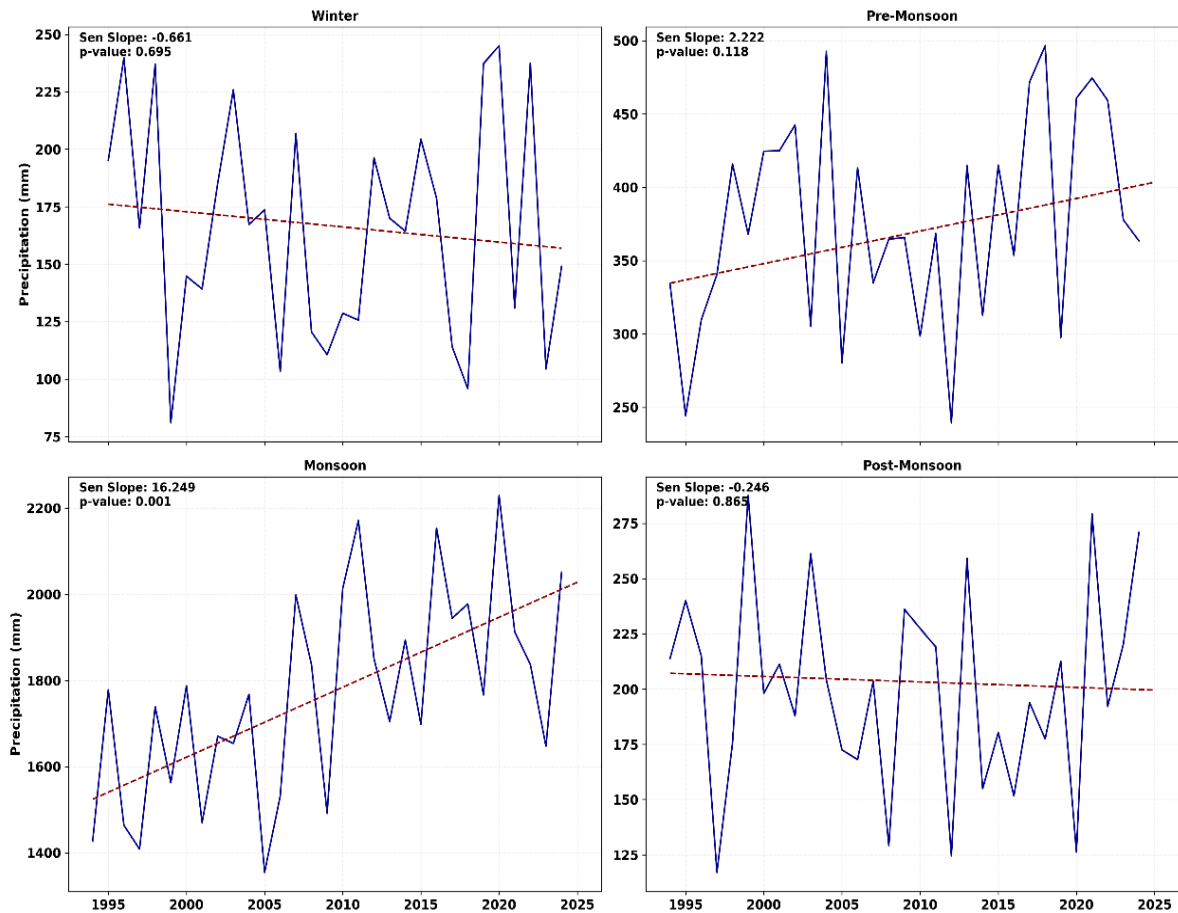


Figure 6: Seasonal precipitation trend from 1995 to 2024

### 3.3 Discharge trend

The statistically significant trend of discharge was observed with Sen's slope of 1.512 m<sup>3</sup>/s per year and a p-value of 0.0104, between 1995 and 2024 as illustrated in Figure 7. The trend line exhibits an uninterrupted

upward trend in annual discharge over 30 years, despite large year-to-year variations. A few years, such as 2005 and 2023, experienced extremely low discharges, while highs were observed in 2011 and 2021.

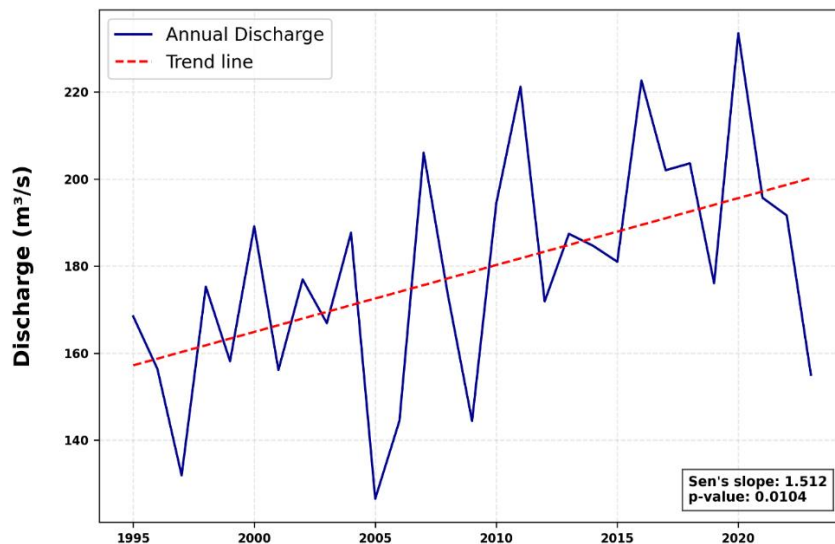


Figure 7: Discharge trend at the downstream of the Dudhkoshi basin

### 3.4 Snow cover and snowline changes

Figure 8 shows the decrease in snow cover at a rate of  $1.84 \text{ km}^2$  per year from 2000 to 2024. While this suggests a steady drop, the trend is not statistically significant with a p-value of 0.183. Snow cover is

affected by multiple interrelated factors. Snow cover varied a lot from year to year, reaching its highest in 2013 and falling sharply after 2015. The negative slope shows a decline, but due to the insignificance, the result is uncertain.

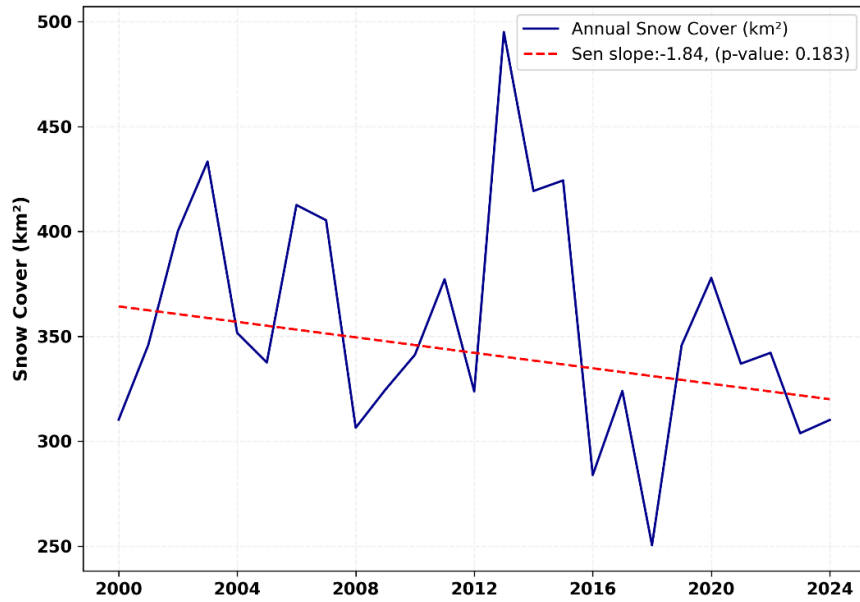


Figure 8: Annual snow cover of Dudhkoshi basin from 2000 to 2024

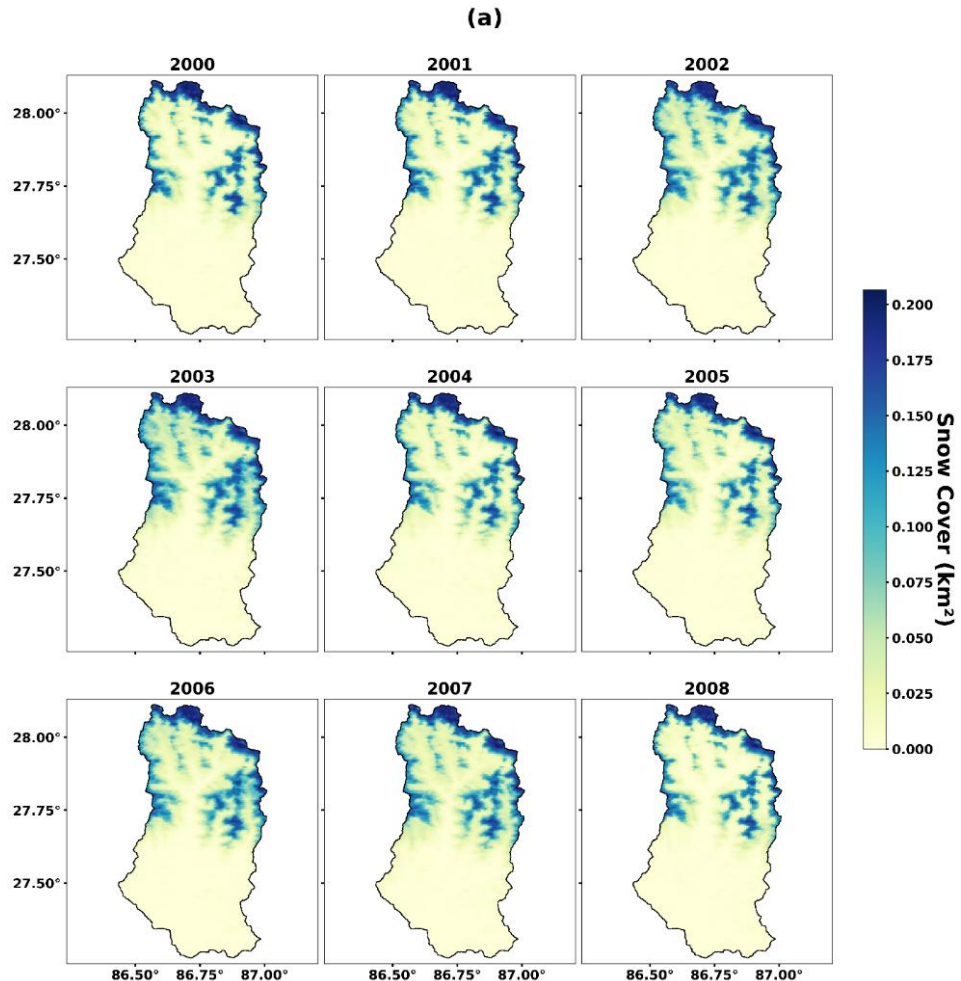
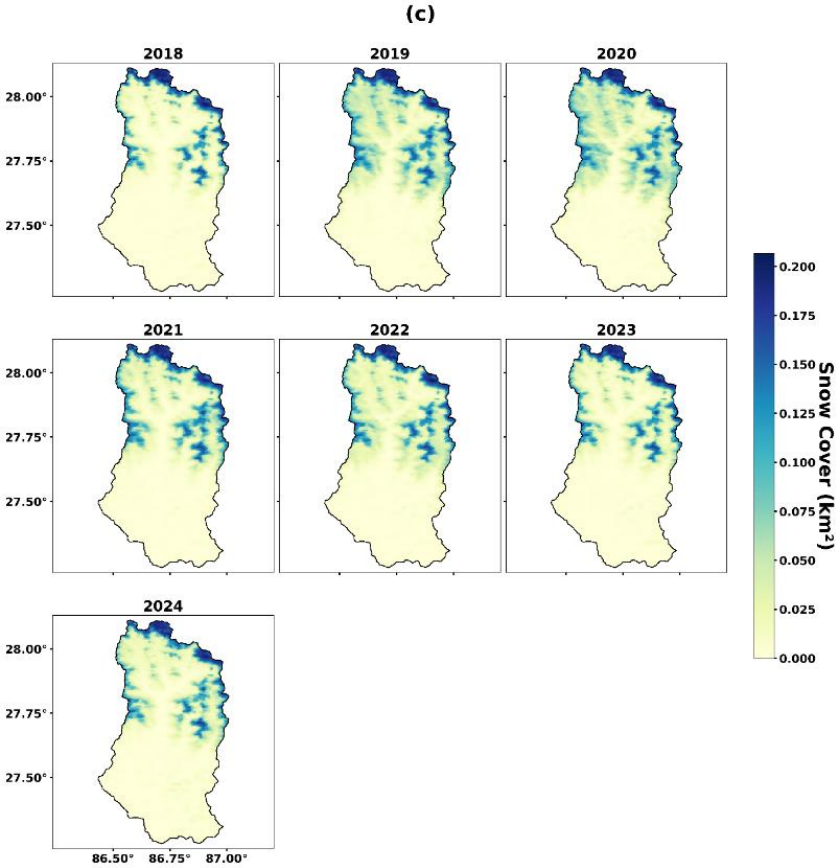
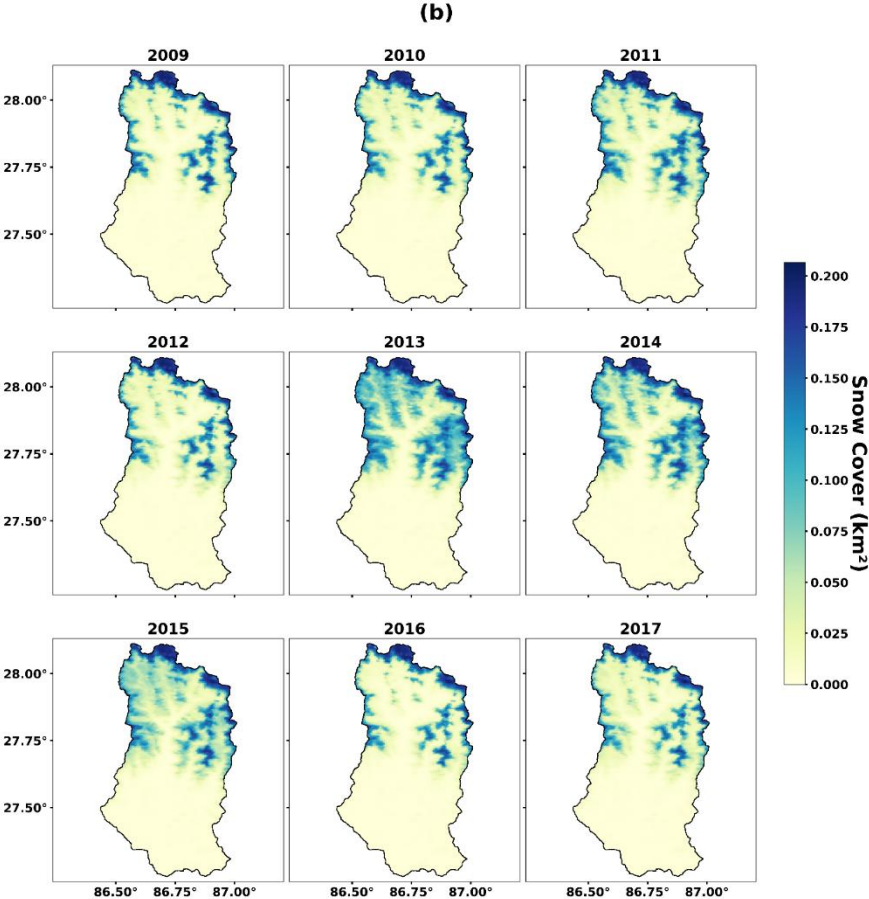


Figure 9(a): Snow cover area of Dudhkoshi basin (2000 to 2008),



Spatial distributions of snow cover for each year from 2000 to 2024 of Dudhkoshi basin presented in Figure 9 indicate that every year's area covered with snow is extremely low, with a mean value of approximately 0.03 km<sup>2</sup>, and with an extremely low interannual variability (standard deviation ~0.01 km<sup>2</sup>) and an extremely narrow range of 0.02 - 0.04 km<sup>2</sup>. Linear trend analysis shows a very minor slope (~0.00 km<sup>2</sup>/year)

with a poor coefficient of determination ( $r^2 = 0.117$ ) and an insignificant p-value of 0.0944, suggesting that there is no statistically significant long-term change in snow cover over these 25 years. These results suggest that snow-covered areas within the basin, clearly limited to high-altitude terrain, have been relatively unchanged during this period, suggesting minimal interannual and long-term variability in snow extent.

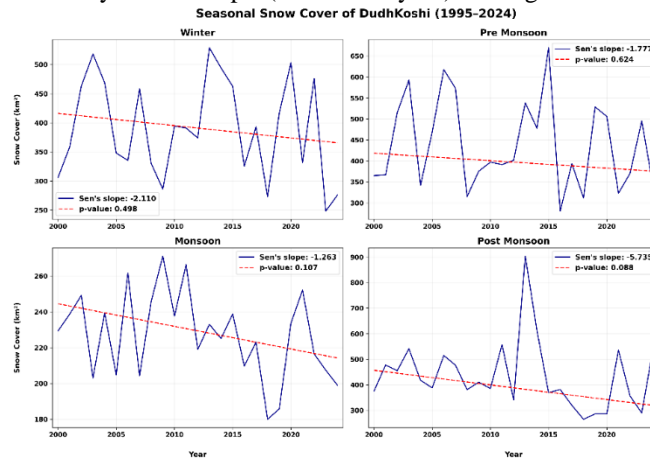


Figure 10: Trend of seasonal snow cover changes from 2000 to 2024 in the Dudhkoshi basin

Snow cover has been decreasing in all seasons, which is clearly represented by the Sen's slope in the basin with the biggest drop seen in winter as shown in Figure 10. Winter shows a Sen's slope of -2.110 km<sup>2</sup> per year, while the pre-monsoon, monsoon, and post-monsoon have slopes of -1.777 km<sup>2</sup>/year, -1.263 km<sup>2</sup>/year, and -5.735 km<sup>2</sup>/year respectively. However, none of these trends are statistically significant, as the p-values are 0.498 for winter, 0.624 for pre-monsoon, 0.107 for monsoon, and 0.088 for post-monsoon, indicating that the snow cover is a function of multiple interdependent factors.

The annual snowline elevation in the Dudhkoshi basin for the period 2000 to 2024 shows a general increasing trend (Figure 11), with a Sen's slope of +9.57 m/year, which indicates that the average snowline is increasing by approximately 9.57 meters per year. The trend is not significant with p-value = 0.070, but the persistent increase and relatively low p-value suggest a significant, if unproven, increase in snowline elevation.

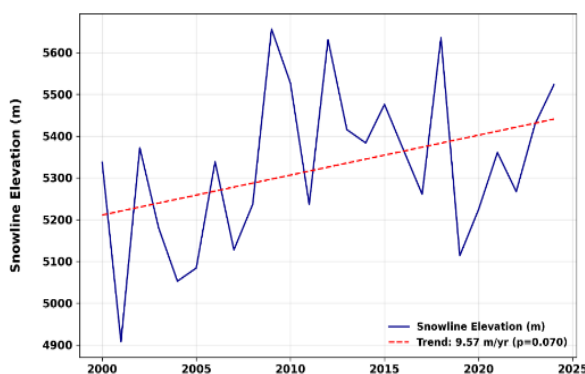


Figure 11: Annual snow line elevation from 2000 to 2024 of Dudhkoshi basin

### 3.5 Correlation between climate variables and cryosphere indicators

#### 3.5.1 Temperature and snow cover

The negative relationship between mean annual temperature and annual snow cover was observed in Figure 12 from 2000 to 2024. The correlation coefficient ( $r = -0.46$ ) highlighted a moderate level of negative relationship. The p-value of 0.0199 signified that the relation is statistically significant with a 95% confidence interval of the regression line, which outlines the area where the actual relationship should fall.

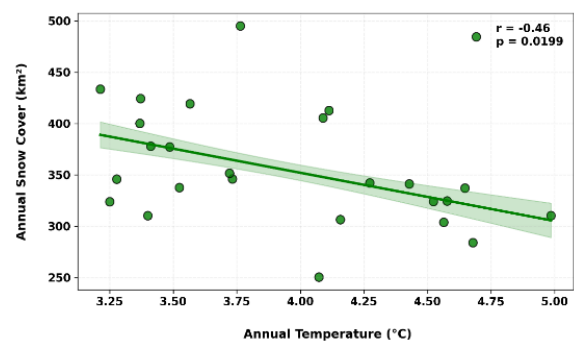


Figure 12: Annual changes in snow cover and temperature

The negative correlation between snow cover and seasonal temperature over the four seasons was depicted from 2000 to 2024, as shown in Figure 13. The strongest correlations were seen in winter with  $r = -0.67$ , p-value = 0.0003, and pre-monsoon  $r = -0.59$ , p-value = 0.0021 seasons, when warming temperatures are strongly correlated with a reduction in snow cover. The monsoon season also has a statistically significant negative correlation ( $r = -0.47$ , p-value = 0.0180), but the correlation is weaker. The post-monsoon season has a weaker and statistically insignificant correlation ( $r = -0.30$ , p-value = 0.1517).

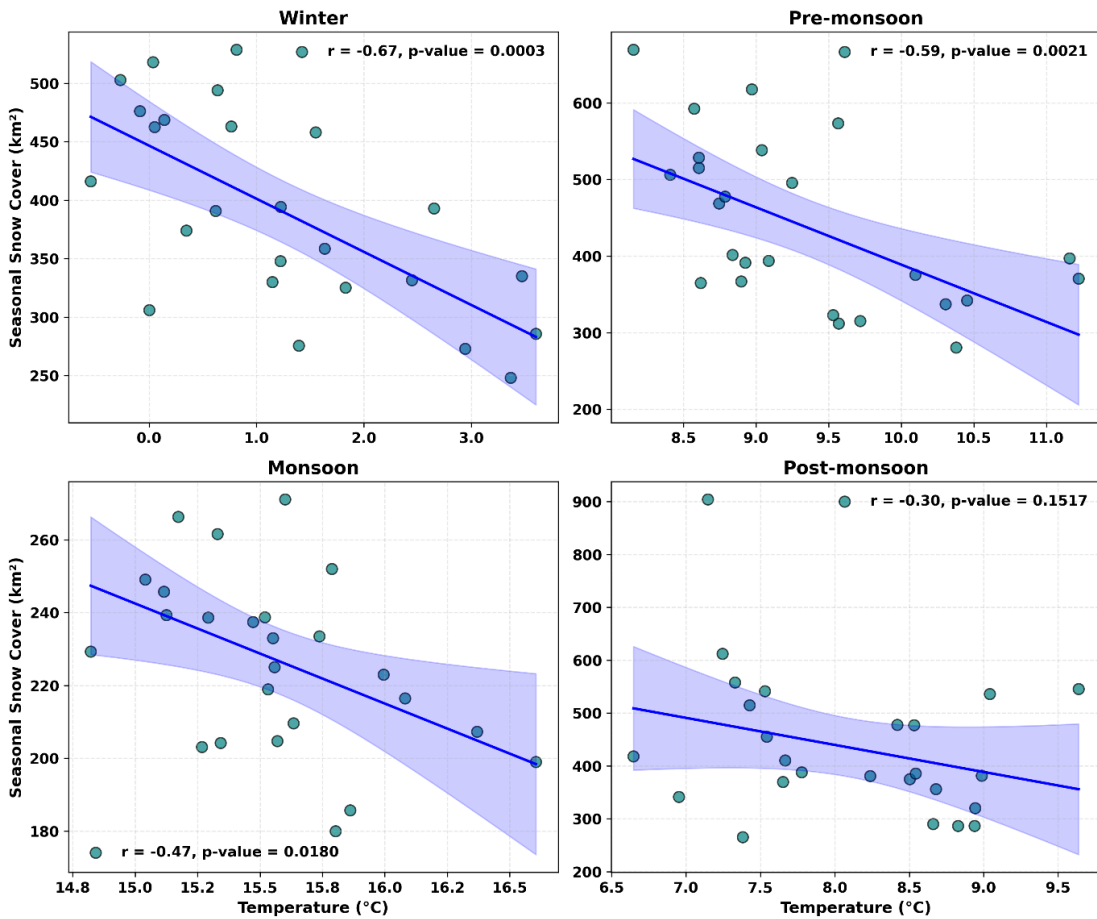


Figure 13: Correlation between seasonal temperature and snow cover

### 3.5.2 Precipitation and snow cover

The relationship between annual snow cover and annual precipitation in the Dudhkoshi basin, as shown in Figure 14, from 2000 to 2024, where the p-value ( $p = 0.6363$ ) and correlation coefficient ( $r = -0.10$ ) show a very weak and statistically non-significant relationship. It indicates that snow cover extent is not influenced by annual precipitation much. The trend line also indicates a weak relationship over 25 years. While both annual precipitation and snow cover are highly variable from one year to another, there is no apparent pattern or significant correlation. While both annual precipitation and snow cover are highly variable from one year to another, there is no apparent pattern or significant correlation.

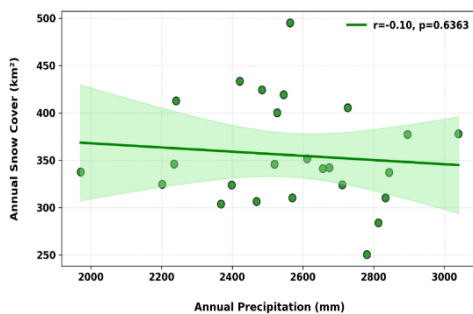


Figure 14: Annual snow cover and precipitation

There is a statistically significant and strong positive relation during the winter season ( $r = 0.71$ ,  $p = 0.0001$ ),

as shown in Figure 15, which indicates that precipitation is a vital driver of snow cover for the season. The post-monsoon season also shows a statistically significant positive correlation, though weaker ( $r = 0.47$ ,  $p = 0.0171$ ), that precipitation in the late period contributes to snow cover. Monsoon ( $r = -0.14$ ,  $p = 0.5021$ ) and pre-monsoon ( $r = -0.20$ ,  $p = 0.3288$ ) seasons, on the other hand, show no significant relationship with snow cover.

### 3.5.3 Temperature and snow line

The relationship between mean and annual temperature and annual snowline elevation for the years 2000 to 2024 is shown in Figure 16.

The analysis revealed a statistically significant positive relationship, as indicated by a correlation coefficient of 0.69 and a p-value of 0.0001 between mean annual temperature and annual snowline. The

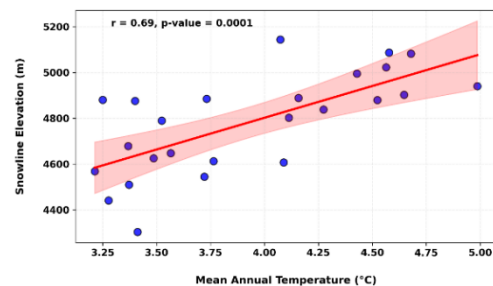


Figure 16: Annual snowline changes with temperature from 2000 to 2024

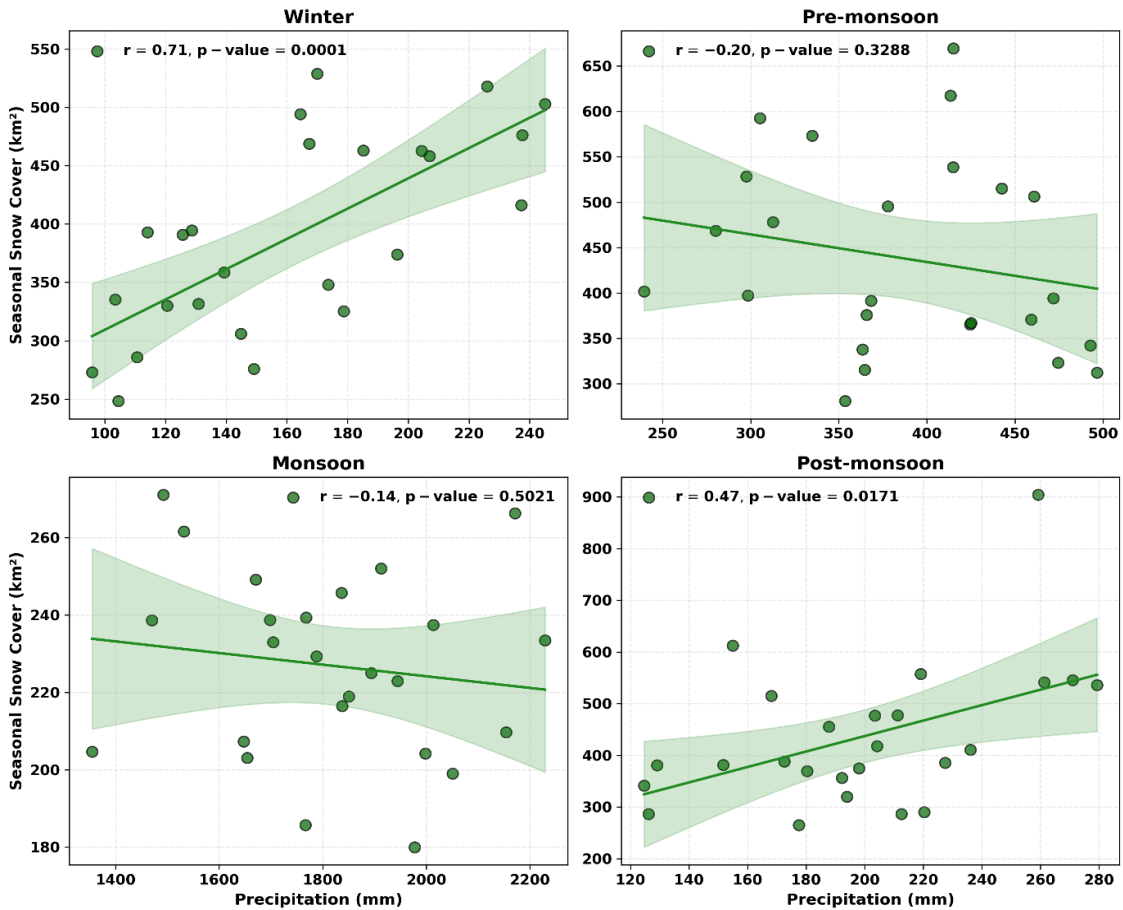


Figure 15. Correlation between seasonal precipitation and snow cover

trend line suggests that rising temperature is one of the key factors in the upward migration of the annual snowline. The shaded area represents the confidence

interval, for 95% confidence limit, showing the likely range of this relationship.

### 3.5.4 Precipitation and Snow line

The linear relationship between the annual precipitation and annual snowline elevation in Figure 17 indicates a very weak negative correlation coefficient ( $r = -0.16$ ). The p-value of 0.452 is well above 0.05, confirming that the trend seen here is not statistically significant. The confidence interval around the regression line highlights a very high degree of uncertainty and a lack of a strong, definite relationship between the variables.

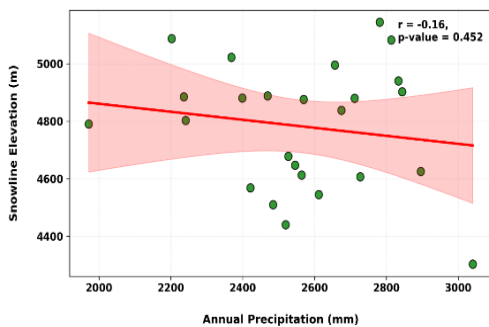


Figure 17: Precipitation vs snowline elevation from 2000 to 2024

### 3.5.5 Discharge and snow cover

The relationship between annual discharge and snow cover from 2000 to 2024 (Figure 18) showed that the discharge values range between approximately 120 m<sup>3</sup>/s and 230 m<sup>3</sup>/s, while snow cover varies from about 250 km<sup>2</sup> to 500 km<sup>2</sup>.

The fitted regression line indicated a very weak negative relationship between discharge and snow cover, with a correlation coefficient ( $r = -0.05$ ). The associated p-value (0.8176) is not statistically significant, indicating that variations in snow cover do not show a meaningful influence on discharge during the study period.

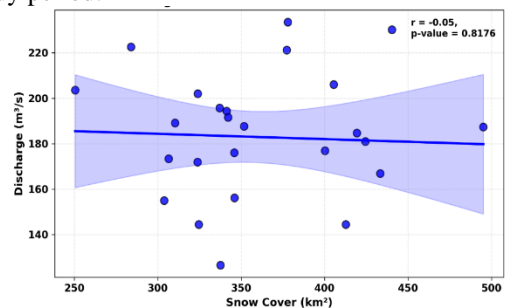


Figure 18: Changes in discharge with snow cover from 2000 to 2024

### 3.5.6 Seasonal discharge and snow cover

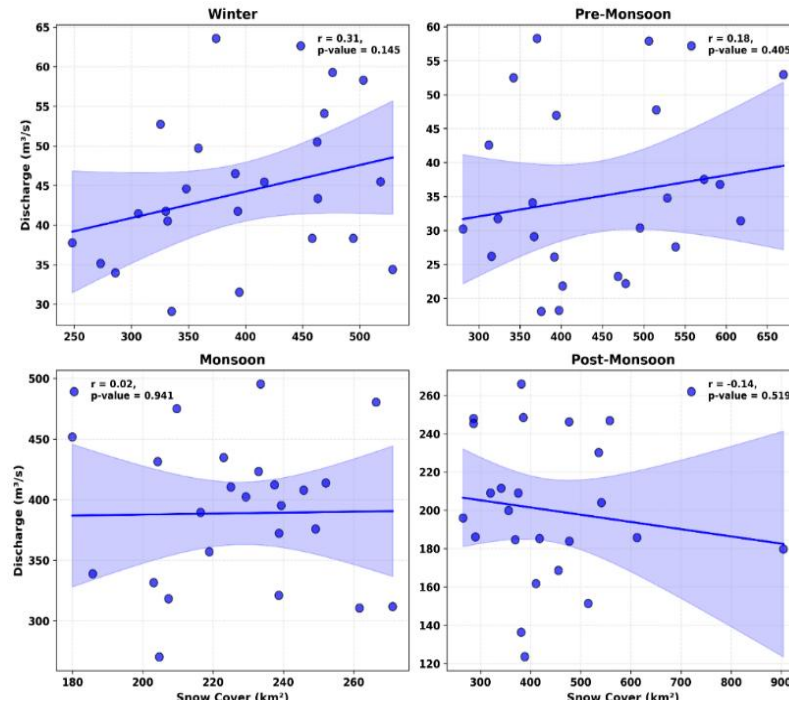


Figure 19: Seasonal changes in discharge with snow cover from 2000 to 2024

The seasonal relationship between snow cover and discharge is shown in Figure 19, where there is no straight relationship, as indicated by the very low correlation coefficients. The value of the correlation,  $r = 0.02$ , for the monsoon season, indicates a practically non-existent relationship. The pre-monsoon and winter seasons have weak positive correlations of  $r = 0.18$  and  $r = 0.31$ , respectively, but the post-monsoon season has a weak negative correlation of  $r = -0.14$ . The trends observed are not statistically significant, as it is evident from the p-values of all four plots, ranging between 0.1450 and 0.9410 and far above 0.05.

### 3.6 Multiple Correlation

#### 3.6.1 Relationship between temperature, snow cover, and discharge.

The scatter plot in Figure 20 illustrates the relationship between temperature, snow cover, and discharge. Snow cover ranges from approximately 250 km<sup>2</sup> to 500 km<sup>2</sup>, while temperature varies between 3.2°C and 4.6°C. The colour scale represents discharge, which lies between about 130 m<sup>3</sup>/s and 230 m<sup>3</sup>/s. The correlation coefficient ( $r = 0.073$ ) indicates a very weak positive relationship between temperature and snow cover. However, the p-value (0.9455) shows that this relationship is statistically insignificant, suggesting no meaningful association among temperature, snow cover, and discharge during the study period.

#### 3.6.2 Relationship between precipitation, snow cover, and discharge

Figure 21 shows, the multiple correlation between precipitation, snow cover, and discharge showed a very strong combined relationship, as reflected by a high correlation coefficient ( $r = 0.973$ ). Furthermore, the p-

value of  $3.569 \times 10^{-14}$  indicates that this relationship is statistically significant.

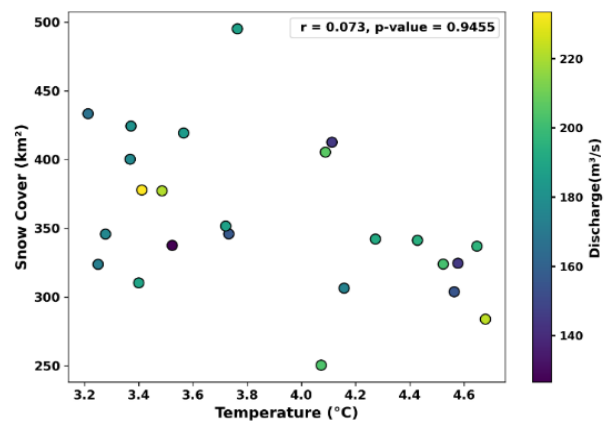


Figure 20: Multiple correlation between temperature, snow cover, and discharge

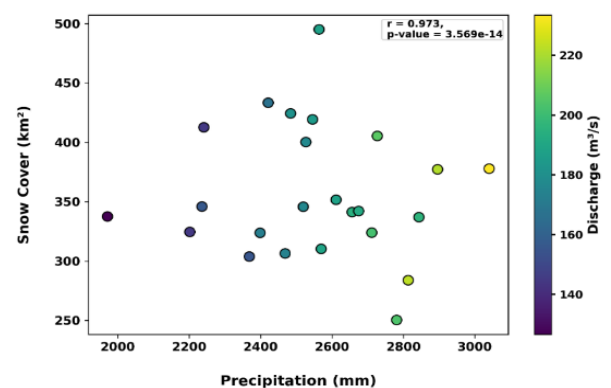


Figure 21: Multiple correlation between precipitation, snow cover, and discharge

#### 4 Discussion

The results from the Dudhkoshi basin highlight important hydroclimatic changes over the past three decades. The mean annual temperature increase (+0.04 °C/year) is large and is in line with previous reports of Himalayan warming, implying a general change in the temperature pattern of the basin. The monsoon and post-monsoon are especially strongly warmed in the season, whereas winter and pre-monsoon are weaker and more erratic. This type of warming carries significant consequences for snow, the melting of glaciers, and the timing of water supply.

Annual precipitation has also grown sharply (+16.04 mm/year), and the sharp increase is experienced in the monsoon and pre-monsoon seasons also, with the tendency towards a decrease in winter precipitation. This result agrees with other Nepal-wide literature that documents amplification of monsoon precipitation and extremes (Pokharel et al. 2020b; Shrestha et al. 2017). Despite high interannual variability, both dry and wet years, the general trend shows that there is a strengthening hydrological cycle. Streamflow is consistent as the discharge annually grows by +1.5 m<sup>3</sup>/s/year. Such an increase can be explained by the interaction of increased precipitation and warming that makes glaciers and snow melt faster, as observed in glacier-driven basins across the Himalaya (Armstrong et al., 2019b; Nepal, 2016b).

There are mixed signals of cryospheric indicators. The trend of the snow cover is downward (-1.84 km<sup>2</sup>/year), but statistically non-significant with high interannual variability. However, the observed tendency is in line with the global trend, with almost 78 % of the mountain snow cover diminishing under warming and changing precipitation regimes (Notarnicola, 2020). The relationship between snow cover and temperature ( $r = -0.46$ ,  $p < 0.05$ ) is negative, which confirms how sensitive the cryosphere is to warming, which has also been found in other Himalayan basins by Maskey et al. (2011). Meanwhile, the snowline has moved higher by an average of +9.6 m/year, indicating that increased temperatures are pushing snow to higher altitudes, often in line with other recent results in the area at large (Khadka et al., 2020).

In general, the analysis shows that the factors of precipitation, temperature, snow cover, and discharge have close interconnections, although individual relationships are weak. The basin is also turning more rainfall-intensive, and snow and ice contribute a lesser buffering effect, which has consequences for both the availability of water and hydrological extremes. Such a change might increase flood exposure in wet years and reduce resilience to dry years. Although the observed changes agree with the regional climate change projections, uncertainties exist owing to limited records of observation, large interannual variability, and difficulties in tracking snow in complex landscapes. The non-significant trends in the snow cover are partly because of the imprecision of the satellite data, and the alteration of river flow might be affected by human

actions, e.g., it was outside the scope of the current research.

To enhance clarity, future studies need to combine measurements of the balance of glaciers, isotopic studies of the sources of runoffs, and high-resolution climate modelling. There will be a need for long-term surveillance to identify the manifesting climate signals among the natural variations and to explain the changing combination of rainfall, snowmelt, and glacier melt contributions in the Dudhkoshi basin.

#### 5 Conclusion and Recommendation

This study evaluated the long-term relationships among temperature, precipitation, snow cover, snowline elevation, and river discharge in the Dudhkoshi Basin, one of the most glacially covered and hydrologically important Nepalese catchments. It offers a very clear picture of how climate variability and change are remaking water availability in this high mountain setting by combining cryospheric and hydrological insights. The outcomes indicate that there are strong processes of warming (+0.04 °C/year) and precipitation reinforcement (+16.04 mm/year), particularly in the monsoon, and that the river discharge increases steadily (+1.5 m<sup>3</sup>/s/year). Snow cover has a decreasing tendency, though the tendencies are not significant, and this indicates a high variation between years. The fact that the observed increase in the snowline (+9.57 m/year) also emphasizes the sensitivity of the cryosphere to warming despite the uncertainty caused by the limitation of the data in complex terrain.

The correlations indicate that temperature is a strong force of snow dynamics, with strong negative relationships between warming and snow cover and a positive correlation between developing snowline elevation. Although precipitation is obviously a more important factor in discharge formation, its interaction with snow cover is less strong and seasonal, with a tighter connection in winter and post-monsoon months. Taken together, these results indicate that a transformation in the basin in favour of a rainfall-based hydrological regime, decreasing the buffering capacity historically provided by snow and ice. This change directly affects water resources, and the risk of floods is higher in wet years, and resilience is lower in dry years, which is consistent with larger-scale Himalayan and global cryosphere shrinkage.

Notwithstanding these revelations, there are uncertainties which are occasioned by sparse data records, interannual variations, and the inaccessibility of snow products on rugged surfaces by satellites. Change in land use or hydropower operations (as well as other human factors that were not included in this study) also influence discharge responses. To overcome these gaps, the research should, in the future, incorporate both the measurements of glacier mass balance, isotopic studies on the origin of runoffs, and high-resolution climate models. Cryosphere-hydrology interactions can be observed only over long periods, which is essential to identify new climate indicators and improve projections of water availability.

Management-wise, these findings highlight the urgency of the need to prepare for the changing water regimes in the Dudhkoshi Basin. It is essential to strengthen hydro-meteorological surveillance systems, to improve the warning system on floods and droughts, and to include in the plan of water resources the cryosphere-hydrology dynamics. The growing reliance on highly variable rainfall and declining reliability of snow and ice contributions must be considered by basin-wide planning as hydropower and downstream water demands grow. The changing climate will necessitate building resilience by developing adaptive infrastructure, better forecasting, and integrated governance of water to manage the changing water resources of this Himalayan catchment on a sustainable basis.

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