Annapurna's Fading Ice: Unraveling the Implications of Climate Change on Snowline

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Abstract

The Annapurna Conservation Area (ACA), situated in the central part of Nepal, comprises certain portions of the Hindu Kush Himalayan (HKH) region. Because of the increasing temperature patterns and irregular precipitation trends, the snowline is highly influenced and shows irregular shifting. The annual, seasonal, and monthly behaviour of the snowline, relating it to the temperature for the time span of 25 years (2000-2025), is studied. Satellite-based platforms, i.e., GEE, deploying the datasets as MODIS and ERA5-land, and SRTM DEM, are preferred for the study. This study points out that the snowline shifts by 38.46m/°C (R^2=0.10, p value=0.1165) in the ACA. The season-based analysis of the snowline gives significant results, where it was found that summer reveals negative trends (-7.47m/yr, p-value=0.026) and winter (slope=73.68m/°C, R^2=0.53, p-value=0.00) shows strong positive correlation with temperature, whereas the trend was a bit insignificant with a higher p-value in the case of annual snowline elevation. The minimum temperature of ACA is increasing, as a result, the snow persistence is decreasing, impacting the overall hydrological systems. Because of these cryospheric fluctuations, the downstream region's communities are immensely affected. Declining pure water resources, ecological instability, agricultural loss, fluctuating surface runoff, disruption, and downturn in the tourism sector are some of the socio-economic challenges faced by the locals due to accelerating snowline elevation. This study tries to seal the existing information gaps by performing a long-term study of snow dynamics using remote sensing techniques.

Keywords: Annapurna Conservation Area (ACA), cryosphere, hydrological systems, snowline

Introduction

The cryosphere of the earth, where the water is in a frozen state, consists of snow, glaciers, permafrost, ice, ice sheets, etc. in large quantities. The cryosphere has a lead role in monitoring the overall climatic patterns, water resources, ecosystems, and so on (IPCC, 2021). Despite these, the abnormal rise in temperature leading to global warming has had a severe effect on the cryosphere of the Earth. The cryosphere is undergoing rapid changes in terms of mass and volume due to global warming. The effects of the amplified and over-warming are directly observed in the high-elevation areas, especially in the high mountain regions (Huss & Hock, 2018). This unwanted rise in temperature leads to overall glacier mass loss worldwide, and on the other hand, it leads to the regular deficit of seasonal snow cover across the globe in highly elevated zones, affecting the entire hydrological cycle. These hazards affect the availability of water and play a crucial role in the rise of the sea level (IPCC, 2023).

The Hindu Kush Himalayan (HKH) region comprises 8 countries and extends over 3500 KM and is referred to as the third pole. After the Arctic and Antarctic regions, the HKH region contains the maximum amount of water in frozen form, which is more than 15% of the entire world's ice situated outside the polar regions (Bolch et al., n.d.). Due to the presence of huge reservoirs of ice, the HKH region is warming significantly. The rate is a bit higher compared to the average of other parts of the world (ICIMOD, 2019a; Karki et al., 2020). This accelerated trend of warming interferes with the glacial melt rate. It also influences the regular patterns of precipitation in the form of snow i.e. snowfall decreases and leads to an increase in the amount of rainfall (Chaulagain, 2009). The Himalayas are the major sources of water in South Asia, as around 1.8 billion people rely directly or indirectly on them (Immerzeel et al., 2010).

The snowline, the elevation above sea level where the snow can be found throughout the year, is the key indicator that represents climate change. The long-term alteration or rise of the snowline in the mountain region signals climate change. This snowline lies above the treeline and marks the beginning of perpetual snow. In the present context, there is a gradual shifting of the snowline towards the higher-elevation regions of the Himalayas. The Annapurna region, home of several 8000m high mountains, is facing the problem of elevating snowlines, disrupting the entire hydrological cycle of the central Himalaya. This also disturbs the water distribution and availability of the foothills region and entire ecosystem. The snow cover area and snow persistence are reducing day by day, which clearly marks that the climate is changing. The deceleration of SCA, SP, and the acceleration of SLA is a serious issue that might cause an enormous threat to the livelihood and ecosystem not only in Nepal but to the entire world. Similarly, global warming causes the ablation and retreat of glaciers across the globe, affecting the surface and subsurface runoff in different regions and seasons (Shrestha et al., 2019). The consequences are directly observed in hydrology, biodiversity, and also on hydropower generation. Besides these, glacial lake outburst floods(GLOFs), avalanches, landslides, debris deposition, etc, are the other natural impacts developed by the change in the cryospheric regions (ICIMOD, Antarctic Glaciers, 2025). The rise of the ELAs illustrates that the rate of accumulation of snow and ice is less compared to the ablation of ice of glaciers annually, indicating a negative mass balance. With the motive of saving the glaciers worldwide and reducing the implications of climate change on the Himalayas, 2025 is celebrated as the International Year of Glacier Preservation (IYGP), while 21 March 2025 is regarded as the first official World Day for Glaciers.

All these changes occurring in the mountainous region are tracked closely using the digital technique in the form of Remote Sensing (RS) and Geographic Information System (GIS), MODIS, Landsat, and Sentinel are some of the satellite datasets from the Google Earth Engine platform that are used in tracking snow cover areas and in analyzing the trends. Similarly, ERA5 is used as a satellite-based sensor to track the trends of temperature from space. Nepal, where there is a diverse topography with the land elevation ranging from 58m to the world’s highest peak, 8848.86 masl, is complicated to manage the automatic weather station in the mountainous region for regular maintenance. This causes large data gaps and is inconvenient for regular use. That’s why in countries like Nepal, with vast topography, satellite-based data are more reliable for carrying out these types of studies. Using the satellite-based platform (MODIS & ERA 5 land), regular data is obtained from 2000 to 2025 and is used to identify the trends of snowline and its relation with temperature seasonally and annually. Therefore, after assessing the results, it will be useful and act as a guide for the respective authority and urge them to implement sustainable practices to preserve and promote the Annapurna region and the whole Himalaya. This will ultimately provide assistance for the downstream region communities in terms of water availability, balance the ecosystem, support the biodiversity, and mainly enhance tourist flow rates in the Annapurna region, supporting the economy of locals and the whole country.

Objectives

General Objective

- To determine the implications of rising temperatures on the snowline of the Annapurna Region.

Specific Objective

- To find out the annual trends of snowline and temperature in the Annapurna Region.
- To identify the seasonal variation of the snowline with temperature in the Annapurna Conservation Area.

Significance of the Study

Understanding the snowline and snow cover dynamics in the mountainous region of Nepal is very fruitful in every aspect, as they are the tangible effects of climate change. The majority of the global study focuses mainly on glacier dynamics and glacial retreat, while very few highlight snowlines. As Nepal is a mountainous country, the study of the reflexes shown by the shifting of the snowline in response to rising temperatures is essential. This study provides a consequential contribution to understanding the implications of climate change, primarily rising temperature, on the snowline of the high mountainous environment within the Annapurna region.

By combining the datasets of GEE, typically MODIS (offering snow cover data) and ERA5 land (offering 2m air temperature), this study focuses on sealing the research gap by analyzing the relation between snowline and temperature. GEE is a cloud-based platform and aids with diverse geospatial data, while statistical techniques like Regression analysis, Mann Kendal test, and so on assist in finding the trends and correlation between the parameters, leading to meaningful and applicable results. Using the satellite-based platform, this research aims to support precise outcomes in the cryospheric field, where complex topography is regarded as a major problem while carrying out research. Regular depiction in the SCA disturbs the overall hydrological pattern in the mountain region, whose consequences are directly seen and faced in the downstream regions. This alteration in temperature influences the cryosphere, affecting runoff, water availability, and the whole biodiversity of the mountain. Though this study only focuses on the regional area, i.e., Annapurna Conservation Area, it aims to offer insights to the global Cryospheric system, assisting in maintaining a sustainable high altitude ecosystem.

Literature Review

Over the past few decades, climate change has caused diverse effects mainly on the HKH region, creating a vast transformation in the cryosphere. The studies under these phenomena highlight accelerating snow line altitude (SLA) and decelerating snow cover area (SCA) as the directly observed symbols for climate change. This is clearly highlighted by Pandey et al., 2024), using satellite-based images of Landsat and Sentinel, which suggests a rise in the elevation of the snowline over the past four decades by 150m in one of the basins of India, named the Pindari River basin. This study illustrates that the seasonal variation of the snowline and glacial retreat is highly controlled by the global warming trends. Likewise, the study conducted by Manandhar et al. (2025) on Langtang Basin, lying in central Nepal, for the timespan of 36 years (1988-2024) using Google Earth Engine (GEE) and normalised difference snow index (NDSI) to measure SCA along with snowline. They sum up with the finding of reducing snow cover area at a rate of 3.7km^2 per year, approximately, and the 2.24m rise in snowline per year. They also conclude that these alterations were directly related to the shifting in the precipitation patterns and increasing average annual temperature, respectively.

Salerno et al. 2016 carried out a study in Annapurna Conservation Area (ACA), regarding the glaciers, between 2000 and 2016. This study illustrates that the retreat rate of glaciers varies in response to the local climatic patterns, elevation, and other aspects. Also, the behaviour of snow and glaciers differs with respect to climate change, even though they are within the same local region. Similarly, on highlighting the cryospheric changes in the upper Karnali Basin of Nepal, it is found that the dynamics of the snow and glaciers cover solely rely on climatic variation and land topography (Ghimire et al., 2025). In relation to other studies performed within Nepal (Shrestha et al., 2022, Kulkarni et al., n.d.), they promote the use of satellite-based remote sensing techniques to visualize the long-term trends of climatic variations and to highlight the cryospheric thresholds.

In order to monitor the trends of snow and glaciers within the complex topography like the Himalayas, the advancement of automatic methods is a must. The development of such a technique by Racoviteanu et al. (n.d.) for the estimation of SLA over the Eastern Himalaya and Karakoram is found to be more accurate and improved compared to that of traditional methods of visual interpretation.

The regular study of snow and glaciers is crucial for assessing and understanding the status of water availability. ICIMOD is contributing regularly and continues with the research on glaciers and snow platforms. Based on the studies, it highlights a loss of around 15-18% of the entire cryosphere of Annapurna Conservation Area since the 1980s (Bajracharya et al., 2014; ICIMOD, 2019). On the flip side, ELA, which symbolizes the health of glaciers, is seen to be accelerating to higher elevations in the Annapurna region. Here on average, approximately 5-10m of ELA is reported to be increasing per decade (Thakuri et al., 2019).

The trends of global warming are increasing day by day due to both natural and human-induced effects, and the consequences are seen in the HKH region. According to Philippus Wester et al. (n.d.) in their study, the HKH Assessment highlights that there will still be a rise of the HKH region by a minimum of 1.8°C even though the entire warming of the globe lies within 1.5°C, impacting snow cover area and total glacial volume. Similarly, they also pointed out that by the end of the 21st century, the snowline would have risen approximately between 4.4m to 10m per year while the glacier would face a loss of around one-third to two-thirds of the potential volume, respectively. Similarly, previous studies done across Western and Central Himalaya used MODIS and ERA5 datasets of GEE for snowline trends and figured out, within the region, the consistent rise of snowline and the decreased persistence of snow. On applying the Snow Model and SRM on a snow-rich watershed of Afghanistan, it reveals that there were sporadic and extreme flows in pre-monsoon with the trimmed winter discharge caused as a result of shrunk snowpacks and escalating snow line impacting seasonal flow (Abdul Haseeb Azizi & Yoshihiro Asaoka, n.d).

The comparative analysis of diverse studies carried out in other mountain regions, besides HKH, strongly supports these outcomes. Rabatel et al. (2013) and Hanzer et al (2018) both support that the snowline and snow persistence (SP) are more sensitive to changing climatic patterns, i.e., increasing temperature and reducing precipitation. The snowline scales up at the rate of 10-30m per year in the Central Andes Mountains, while the snow cover reduces. Consequently, the observed case was similar to the Alps, where the satellite data performed for the long term showed a similar advancing snowline in response to climatic variability. This supports the idea that the Cryosphere of the entire world is highly sensitive to the rising temperature and shows an inverse relationship.

On the flip side, in Nepal, the shrunken glacier volume and advancing snowline also shows common changes to climatic variability (Thakuri et al, 2019). Most of the studies and research carried out in Nepal mainly deal with glacial behaviour and glacial retreat. Very few, as the number can be counted on the hand, have observed the trends of snow dynamics, i.e., snow line and snow cover area, while the study performed on the Annapurna Region is the lowest of all (Bajracharya et al, 2014, Fujita et al, 2011; ICIMOD, 2019; Bajracharya et al, 2019) are related to the Central Himalaya and solely to the Annapurna region, and some use satellite-based data like MODIS to track the cryospheric changes, mainly the glaciers.

Although these studies provide a great contribution to the cryospheric field, there still exist some gaps. As mentioned, most of them deal with glacial dynamics; the long-term study on the trends of snow dynamics is still lacking in the Annapurna region with complex terrain. Furthermore, the advanced high-resolution remote sensing technique and automated methods are limited and still not deployed regularly in the Annapurna region. The seasonal and spatial instabilities of snowlines are not well defined, making predictions complicated for water accessibility and hydrological ramifications. A deeper exploration is essential to figure out the socio-hydrological influences on downhill region communities, which rely on snowfed rivers and snow melt water, due to snowline alteration.

Taking all these into consideration, this study aims to minimize these gaps by deploying remote sensing techniques (MODIS and ERA5 land) and Digital Elevation Models (DEMs) to inspect the annual and seasonal snowline trends and also the function of temperature in adapting snowline in the Annapurna region from 2000 to 2025. By interrelating these, this study desires to elaborate on the knowledge of cryospheric adjustment to the ascending temperature and aware respective authorities to safeguard the Himalayas and maintain the sustainable mountain ecosystem.

Materials and Methods

Study Area

Among all the protected areas of Nepal, Annapurna Conservation Area (ACA) is considered the largest protected area, spreading over 5 districts of the Himalayan region (Kaski, Lamjung, Manang, Mustang, and Myagdi) with an area of 7629 km² (Shrestha & Aryal, 2011). With an altitudinal variation from the lowland of mid-will of around 790m to the massive range of over 8000m, ACA is the home of the world's tenth highest peak, Annapurna I (8091) (Tuladhar et al., 2021). Some of the other known peaks include Machapuchhre, Gangapurna, Mardi, Annapurna II, III, etc, and have 162 glaciers. With scenic views, rich in biodiversity, the Annapurna region comprises major tourist attractions such as Tilicho Lake (the highest-elevation lake), upper Mustang, Annapurna Base Camp, etc.

The topography arrangements are complex with heterogeneous landscapes containing a variety of ecosystems, with alpine to coniferous forest, steep slopes, deep river gorges, glaciers, and persistent frozen fields (Kattel et al; 2020). The Kali Gandaki Gorge, located between Dhaulagiri and Annapurna Massifs, is the world's deepest Gorge, measuring over 5500 meters in depth, and is topographically and geologically extreme (Bhattarai & Vetaas, 2014).

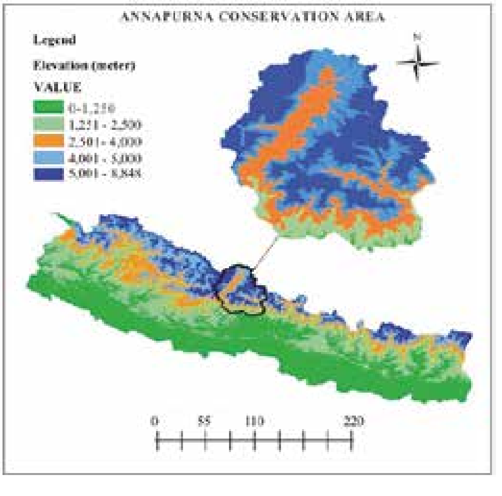
Climatically, this region is highly influenced by monsoon seasons, causing the majority of the precipitation between June to September (Pandey & Bhattarai, 2019)

The form of precipitation varies according to the altitude, as rain is seen at an altitude of approximately 3000-3580m, while above it, the precipitation is in the form of snow. Similarly, Winter is characterized by warmer temperatures with increased precipitation, while winter is cold and dry, characterized by perpetual snow cover over 4000m altitude (Tuldhar et al. 2021; Kettle et al; 2020). These patterns show the region is sensitive to climate variability influencing long-term snow cover and glacial mass balance (Shrestha et al; 2012; Pandey & Bhattarai, 2019).

Considering this crucial information of the Annapurna region, it provides the best-suited context for the investigation of snowline dynamics and temperature variability. These elements have a visible and severe impact on local communities, biodiversity, and regional hydrological systems (Karki & Bauer, 2019; Bhattarai & Vetaas, 2014). Due to these facts, the study of snowline and temperature shifts is mandatory, as previous studies also spotlight the necessity for the perception of these climatic processes throughout the Annapurna region to assist major climatic policies and strategies for creating a sustainable environment within the Himalayan ecosystem.

Figure 1

Land cover map of Annapurna Conservation Area.



Note: The boundary is shown by black polygon

Data and Data Sources

For the project entitled "Annapurna's Fading Ice: Unravelling the implications of climate change on snowline", the data used is Secondary data, which is obtained from remote sensing techniques from different Satellite datasets. The data between the time period of 2000 to 2025-06-30 is used.

MODIS (MOD10A1v6)

The Moderate Resolution Imaging Spectrodiometer (MODIS) is a sensor installed on two different NASA Satellites named TERRA and AQUA. It is operated under the Google Earth Engine (GEE) platform. With a spatial resolution of 500 metres and daily temporal resolution, it has been providing precise, consistent, almost daily Earth observation from 2000 to till date (Hall & Riggs, 2015). MODIS uses Normalised Difference Snow Index (NDSI) for the detection of snow and analyzes the data reflected by the surface, providing daily snow cover globally. Here, MODIS10A1, Terra daily snow cover of version 3, was used to extract the daily snow cover data from 2000 to 2025, assigned with DEM, and the snowline elevation was estimated.

ERA5-Land Climate Reanalysis Data

The dataset named ERA5-land is a satellite-based dataset initially founded by the European Centre for Medium Range Weather Forecast (ECMWF). In this dataset, the data is available from 1981 to the present. Having a spatial resolution of approximately 9km and hourly temporal resolution, ERA5 can be accessed through Copernicus Climate Data Store (CDS) using GEE (ERA5-Land Hourly Data from 1950 to Present). It primarily focuses on land. In this study, ERA5 land is used for the extraction of daily 2m air temperature from the surface between the time frame 2000 to 2025. The hourly data provided was later converted to other time frames as per the requirements of the study. Further, the data was used to operate Mann-Kendall tests and perform trend analysis.

Digital Elevation Model (DEM)

The Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) is the satellite-based dataset provided by NASA and the National Geospatial Intelligence Agency (NGA). With a spatial resolution of 30m and static temporal resolution, it can be accessed through GEE (Farr et al., 2007). The SRTM data was collected a single time in February 2000, which was an 11-day project. The DEM, which is used here for this study, was retained from the SRTM dataset, and it was then superimposed with the map of MODIS snow cover. Finally, the elevation of the snow cap pixels was obtained from 2000 to the present date.

These are the data sources used for the extraction of data in this study.

Tools and Techniques

Tools

The tools used for the analysis of data are mentioned below

Google Earth Engine (GEE)

It is a cloud-based platform used for data processing and geospatial analysis, developed to deal with wide-ranging datasets of the environment effectively and precisely (Gorelick et al., 2017). It was initiated around 2009 and was made available to the public in 2010. Rebecca Moore was the director of GEE. From 2015, it diversified and started including different climatic datasets (such as ERA5, DEM, MODIS, and so on). It allowed students and non-experts to execute complicated remote sensing processes and helped with downloading and processing data in the cloud. In this study, GEE was used to perform an analysis of MODIS (satellite data) and ERA5 (climate data). Similarly, this platform was also used to download the snowline elevation and 2m air temperature for the study.

Geographic Information System (GIS)

GIS tools, i.e., ArcGIS, were applied for the analysis and visualization of snowline elevation spatial data in the Annapurna area. By overlaying MODIS snow cover data on DEMs, snowline altitudes were identified through raster analysis and contouring. The platform also allows various terrain analyses-slope and aspect-and the integration of satellite-derived data, including ERA5 temperature. Another way of identifying spatial patterns of snowline stretching and their temporal changes in snowline elevation involved QGIS plugins and Raster Calculator techniques.

Jupyter Notebook

The environment enables interactive programming for scientific computing and data analysis by merging live code, rich text, and graphics into a single document. Having CSV files imported from GEE, Jupyter Notebook was used for cleaning, pre-processing, and exploratory analysis (Kluyver et al., 2016). It affords stepwise generation of annotated analytical workflows so that hypotheses could be generated and revised iteratively; it also allowed collaborative review of code and discussion of results. Any generated output-whether it was plots, heat maps, or summary statistics, are displayed alongside the methodological discussion, making the study transparent and reproducible (Hunter, 2007).

Statistical Tools (PYTHON)

The formulation of analytical data was made feasible through a set of open-source Python libraries such as Matplotlib, Pandas, Numpy, Scipy, and others, each serving for the scientific data processing requirements (Hunter, 2007; Helsel et al., 2020). Pandas was specifically used to deal with the higher-level table operations and temporal clustering. On the other hand, Numpy was preferred for the array manipulations and numerical operations. Similarly, for the statistical operations, Scipy was used, which performed trend and correlation analysis. Furthermore, Matplotlib was responsible for the standardization of both statistical and visual representation, i.e., snowline elevation trends and temperature data analysis.

Techniques

For the detection of snowline and air temperature above 2m in the Annapurna Conservation Area, several collections, such as Statistical analysis, remote sensing, along climate data analysis, were used. The techniques used in this research are elaborated below:

Snowline Detection Technique

The MODIS Terra snow cover daily data (MOD10A1v6), executed in GEE (a cloud-based platform), was deployed in order to predict the snowline. Here, Normalised Difference Snow Index (NDSI), which is a spectral index, was used to distinguish snow cover area from snow-absent area, where a threshold value greater than 0.4 was used to determine snow cover pixels. Cloud removal, cloud filtering, and pre-processing were used. Only the area having snow cover of more than half of its area was taken into consideration for the calculation of the snowline. For short and long-term variation, the daily image of the snowline was compiled to obtain annual, seasonal, and monthly values. Finally, SRTM DEM was used for the detection of topographic landscape and elevation bands. Depending upon the area having regular snow cover within these bands, the snow cover was analysed, and the snowline elevation was extracted. Thus extracted data was further analysed in Python using Jupyter notebook, followed by various tools such as Mann-Kendall and others, and the graph was plotted.

Temperature Analysis Technique

For the analysis of temperature, ERA5-Land 2-meter air temperature, a reanalysis data having high resolution and a product of ECMWF, was used. It was accessed from the Copernicus climate data store through GEE using JavaScript. The data was filtered according to the study period within the Annapurna region boundary and elevation. After converting the data from kelvin to degrees Celsius, the temporal reduction was performed for daily minimum, mean, and maximum data as annual, seasonal, and monthly data. Furthermore, after the extraction of data, the data was then imported into Python, and long-term trend analysis was performed according to the research requirements with the help of statistical methods.

Statistical Analysis Technique

This is the final step for the analysis of snowline and temperature datasets performed in a Python-oriented library named Jupyter Notebook. To figure out the trend, time series analysis was performed, and the change was detected. Similarly, the Mann-Kendall test, a non-parametric test, was conducted to examine p-values and to define increasing or decreasing patterns. Likewise, linear Regression analysis was executed for the evaluation of linear trends as slope and R^2. With the purpose of figuring out the magnitude of the differences in slope of snowline and temperature, the Theil-Sen slope estimator was carried out. On the other hand, Pearson's correlation coefficient was implemented to examine the mutual dependency of the snowline with temperature. Analysing all these, the graphs, scatter plots, and correlation heat map were plotted with trend lines providing a clear and impactful interpretation and representation of the findings, respectively.

Results

The graphs are plotted according to the temporal variation, i.e., annual, seasonal, and monthly data.

Figure 2

Annual snowline elevation trend (2000-2025).

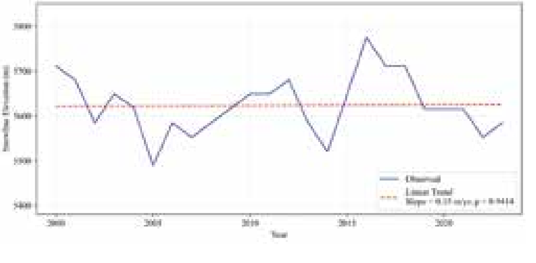
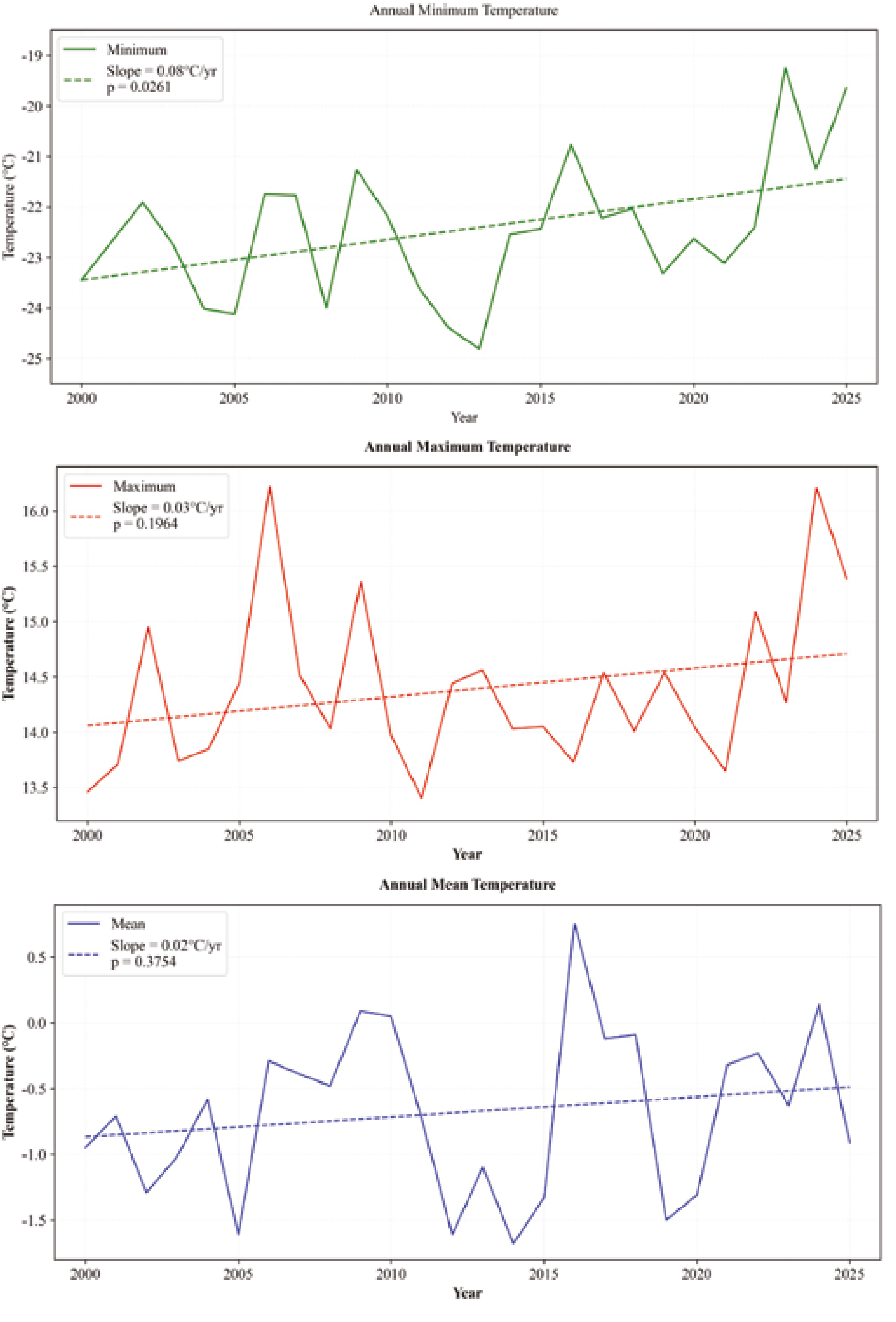


Figure 3

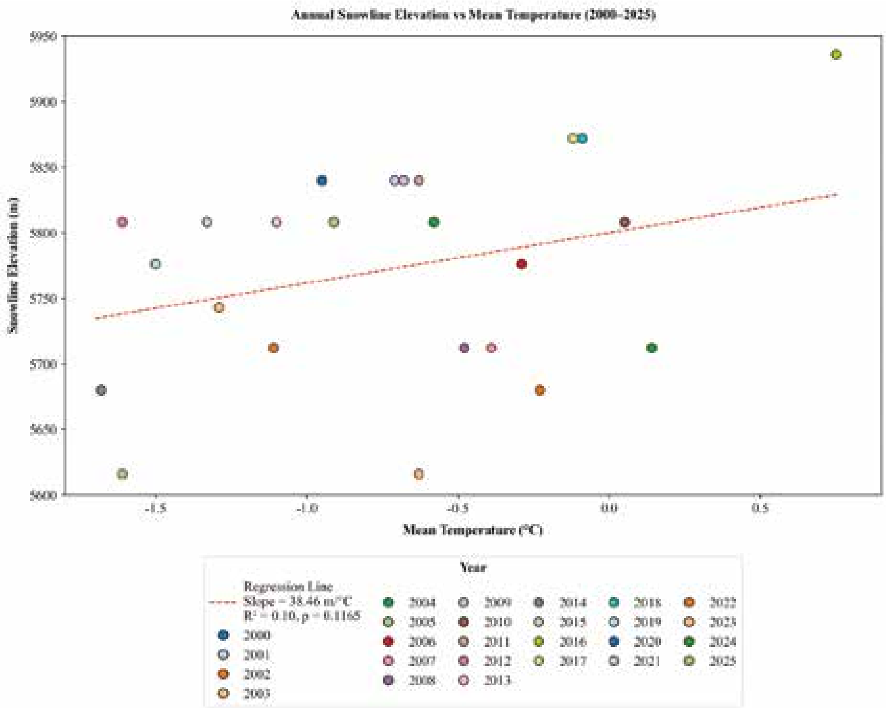
Annual temperature trends (2000-2025).



The figure shows annual shifts of minimum, mean, and maximum temperature between 2000 to 2025, where all show the positive progression of 0.08°C per year, 0.02°C per year, and 0.03°C per year with P values of 0.0261, 0.3754, and 0.1964, respectively.

Figure 4

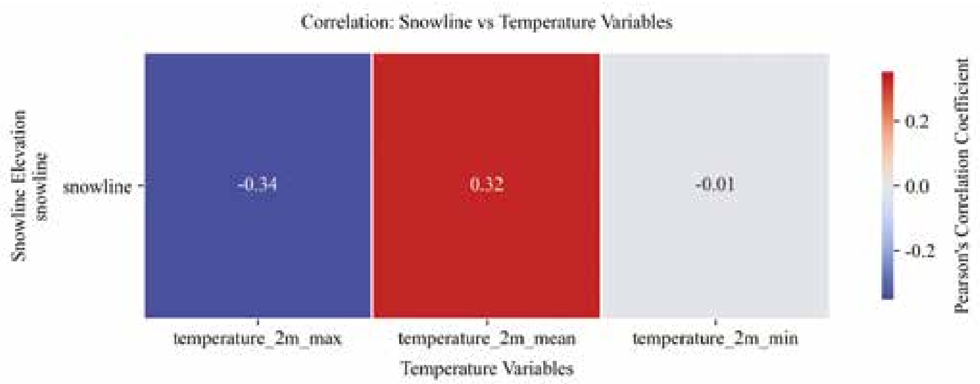
Annual snowline elevation vs mean temperature (2000-2025).



The upper scattered plot between yearly dynamics of snowline and mean temperature, where each year aligns with a special colour code, revealed the slope of 38.46m per °C with 0.10 R^2 and p value of 0.1165, respectively.

Figure 5

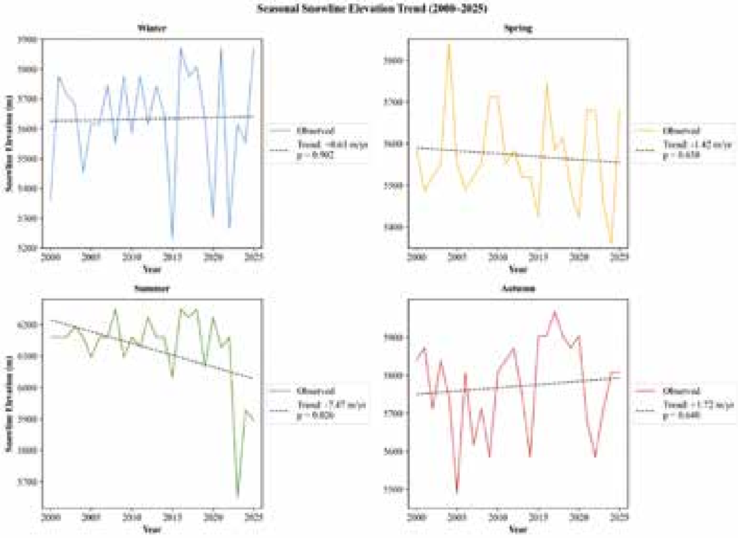
Pearson correlation coefficient heatmap.



As visualized in the upper figure of the Pearson Correlation Coefficient heatmap, it shows that the snowline elevation is correlated with minimum temperature, mean temperature, and maximum temperature, having distinct values of -0.34, 0.32, and -0.01, respectively, signaling that only mean temperature is positively correlated with snowline elevation.

Figure 6

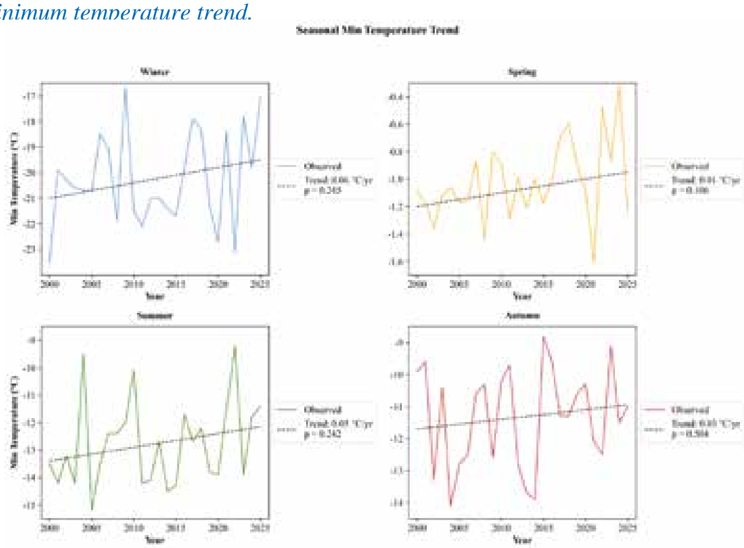
Seasonal snowline elevation trend.



The mentioned chart of seasonal snowline elevation of winter, spring, summer, and autumn depicts the slope of 0.61 m/year and p-value of 0.902 for winter, -1.42 m/year and 0.638 p-value for spring, -7.47 m/year with p-value=0.026 in summer, while autumn shows the slope of 1.72m/yr with 0.640 p-value.

Figure 7

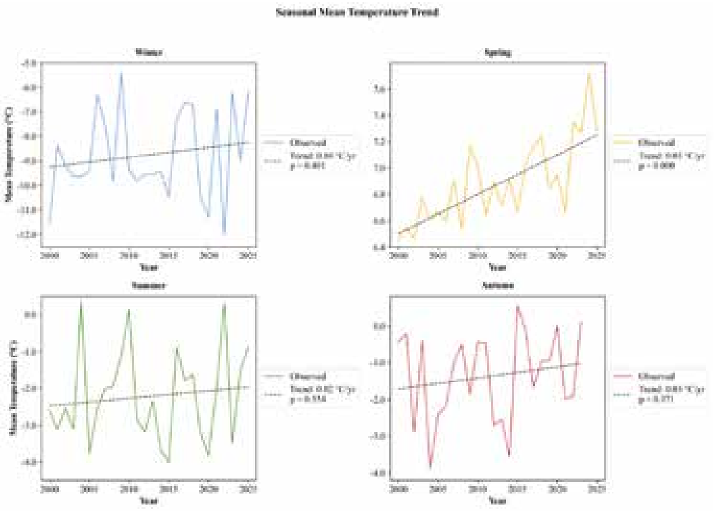
Seasonal minimum temperature trend.



The graph shown above is the comparison of the minimum temperature by season with the trendline. Talking about winter, we can see a rise of 0.06 °C/year and a p-value of 0.245. For spring, the slope is 0.01 °C/year with a 0.106 p-value. Similarly, for summer, the slope is 0.05 °C/year with p-value=0.242. Afterwards, the slope is 0.03 °C/year with a 0.504 p-value for autumn.

Figure 8

Seasonal mean temperature trend

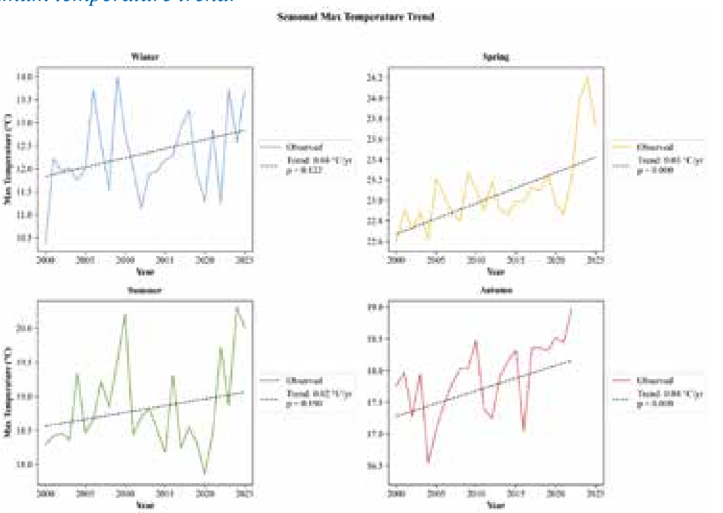


Referring to the graph of mean temperature by season plotted above, it verifies winter slope as 0.04 °C/year and p-value as 0.401, spring's slope as 0.03 °C/year with p-value=0.00.

As of summer, the slope is 0.02 °C/year and p-value=0.554, while it is 0.03 °C/year with p-value =0.371 for autumn.

Figure 9

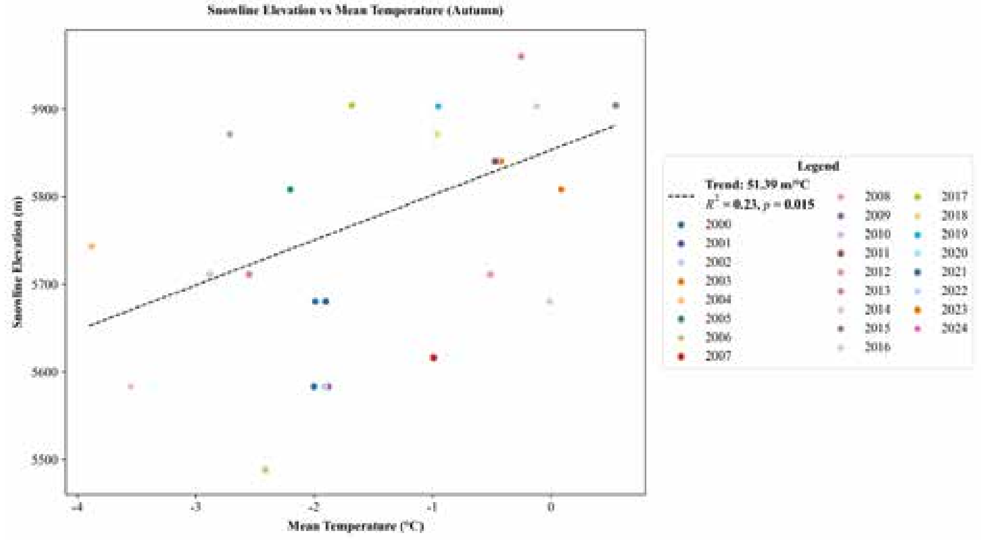
Seasonal maximum temperature trend.



For the graph of maximum temperature by season as illustrated above, there is a rise of 0.04 °C/year and p-value = 0.122 in winter, 0.03 °C/year and p-value=0.00 in spring, 0.02 °C/year and 0.190 p-value in summer, followed by 0.04 °C/year and 0.010 p-value in autumn.

Figure 10

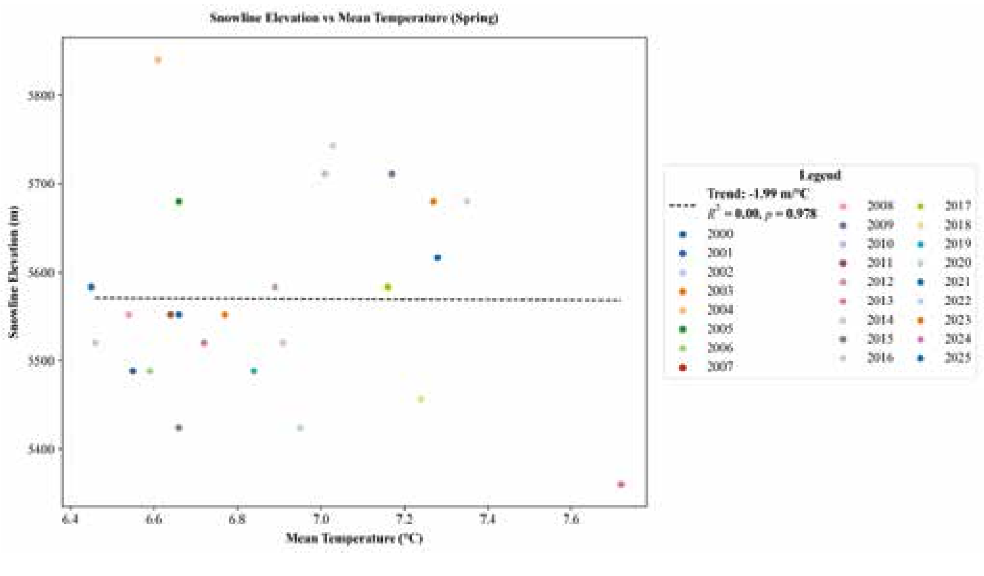
Snow line elevation vs mean temperature (Autumn).



As shown in the scattered plot, the interannual trends between snowline elevation and mean temperature for autumn are plotted, which uncover the slope of 51.39 m/°C and $R^2 = 0.23$ and p-value of 0.015, which shows positive correlation.

Figure 11

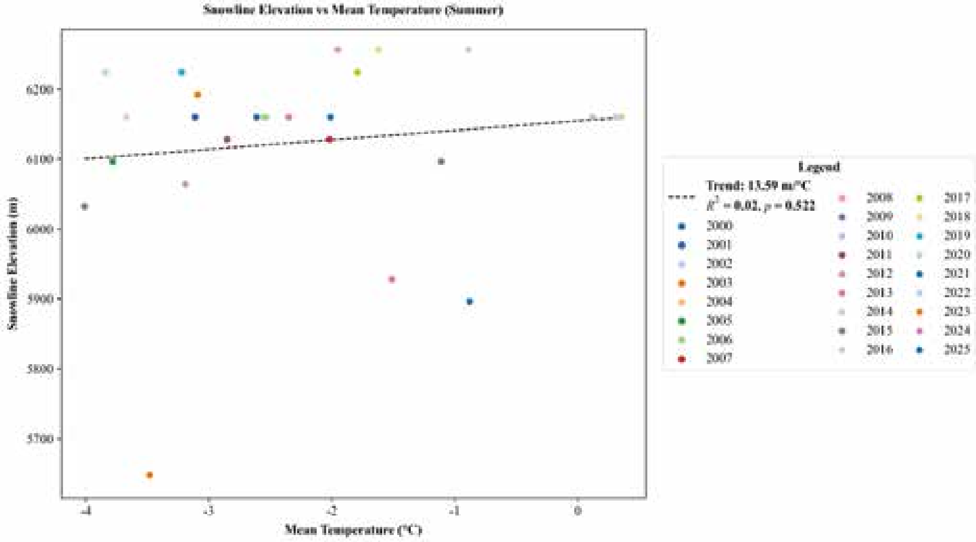
Snowline elevation vs mean temperature (Spring).



The given graph above presents the pattern of snowline elevation vs. mean temperature of the spring season, which reveals a regression slope of -1.99 m/°C and $R^2 = 0.00$ with a p-value of 0.978.

Figure 12

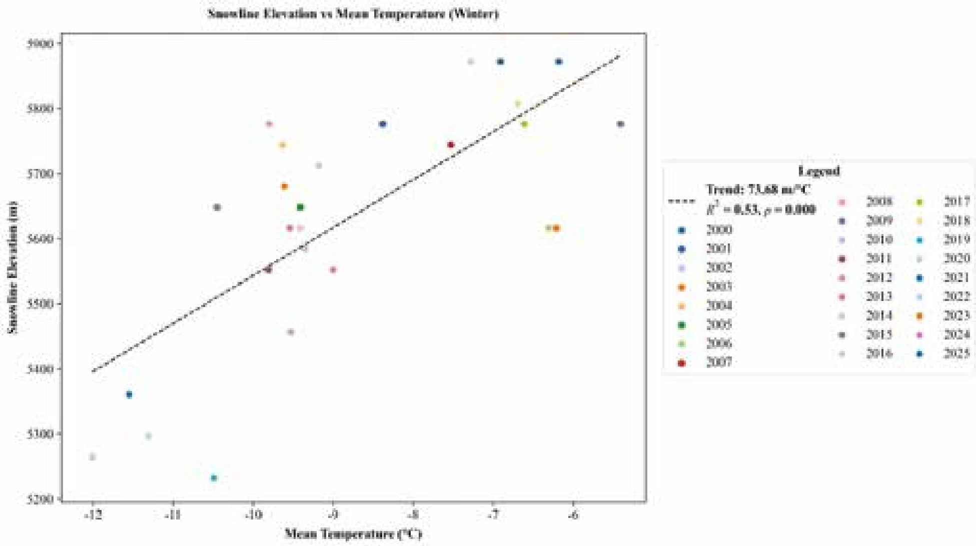
Snowline elevation vs mean temperature (Summer).



The dynamics of snowline versus summertime mean temperature are shown in the graph above, which follows a regression slope of 13.59 m/°C and R2 = 0.02 with a p-value of 0.522.

Figure 13

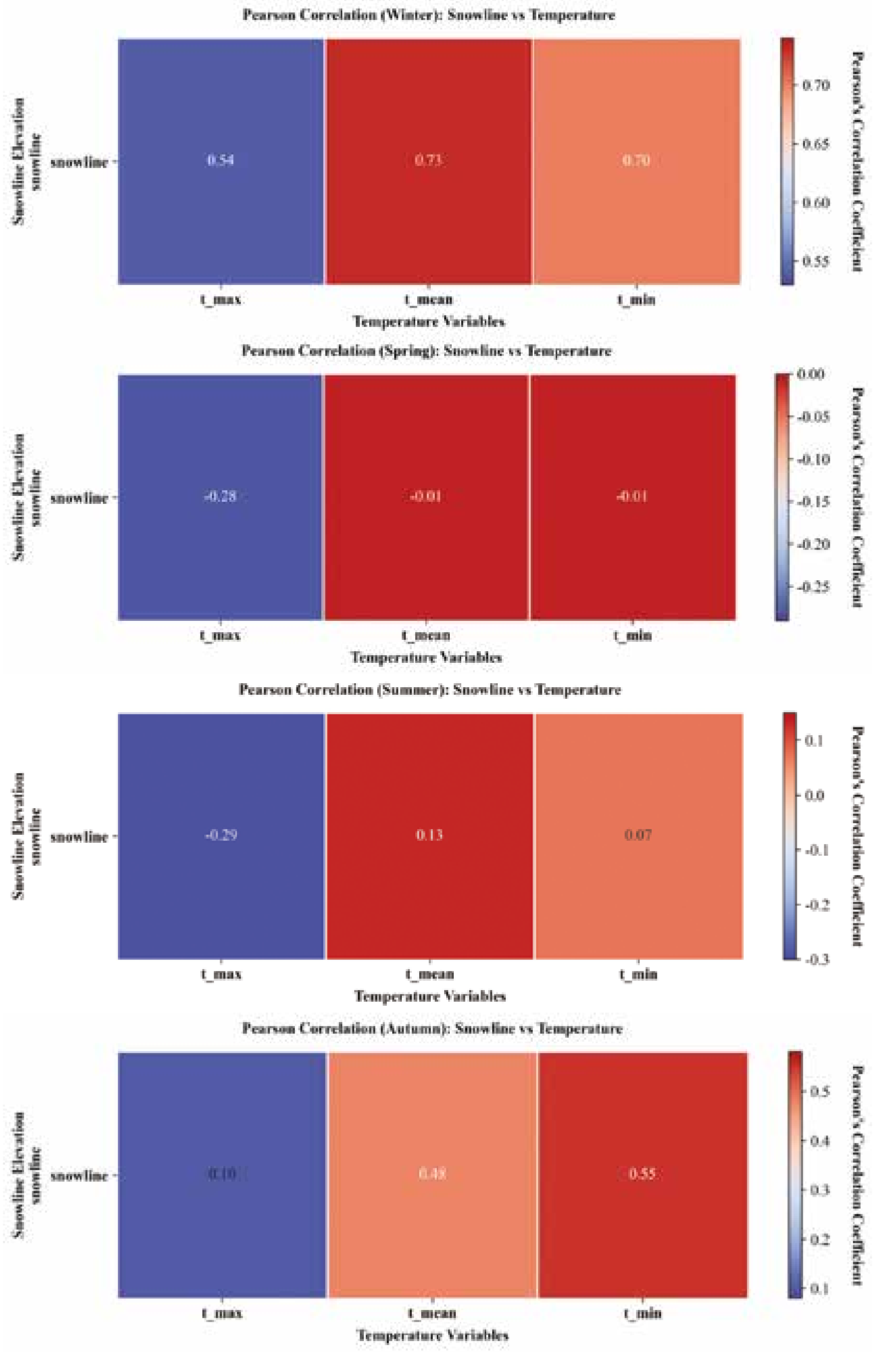
Snowline elevation vs. mean temperature (Winter).



The graph depicts the interannual trends between snowline elevation and mean temperature for winter, with a slope of 73.68 m/°C, $R^2 = 0.53$, with p-value = 0.00.

Figure 14

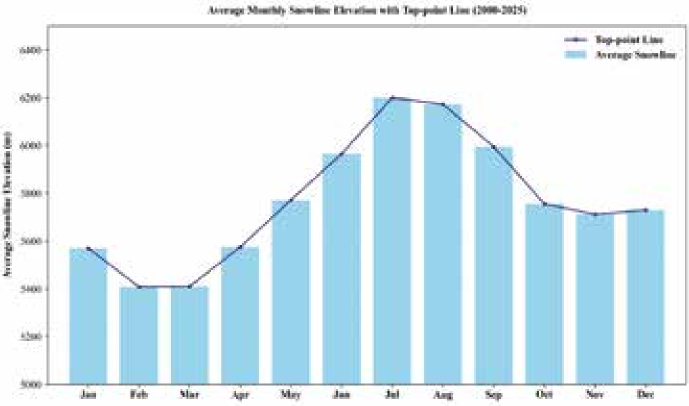
Seasonal Pearson's correlation coefficient heatmap



In the confusion matrix of seasonal data showing the Pearson correlation coefficient heatmap, very strong positive correlation is seen between maximum, minimum, and mean 2-meter air temperature with snowline elevation in other seasons, except in spring, where negative correlation is seen among all temperatures.

Figure 15

Averagem monthly snowline elevation bar graph (2000-2025).



In the plotted diagram of the monthly average snowline from 2000 to 2025, the changes can be seen using the trend line, which is based on the highest point of the bar graph.

Figure 16

Monthly mean temperature trend.

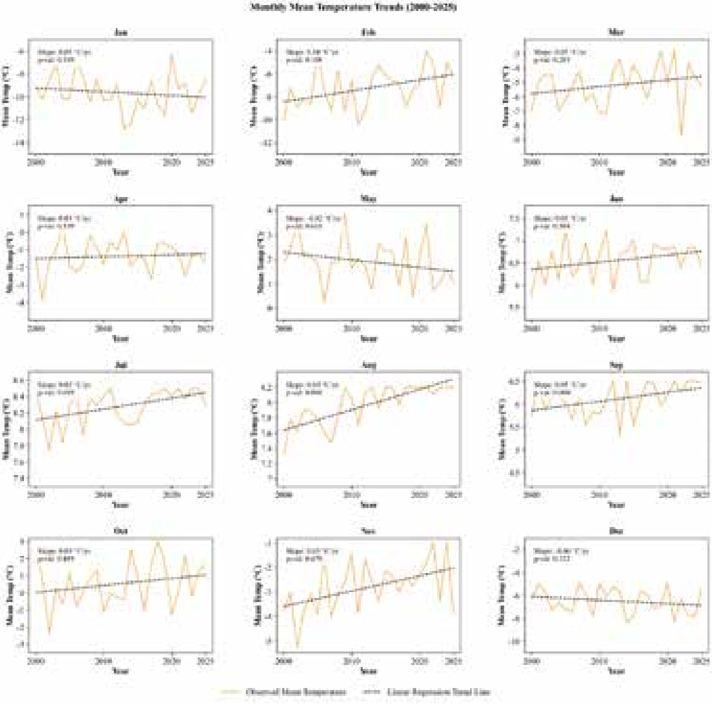
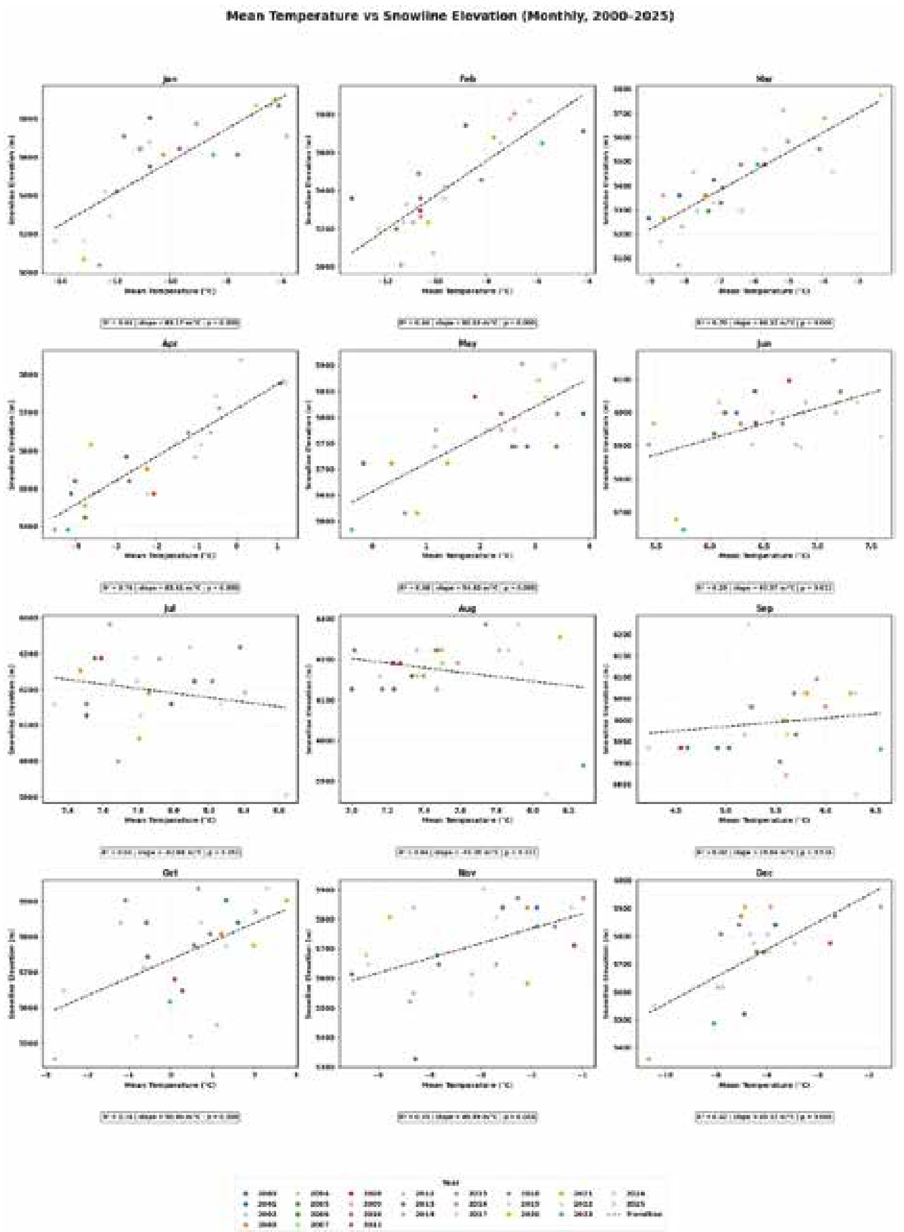


Figure 17

Monthly snowline elevation vs mean temperature scatter plot.



In the figure above, a twelve-panel matrix of scatter plots is displayed, which shows the directional shift in snowline elevation for each specific month in response to monthly mean temperature. Most of the month shows a positive shift, while a few shows negative shift with slopes ranging from 93.37m/°C to -62.84m/°C with R^2 ranging between 0.76 to 0.02 and p-value from 0.000 to 0.516, respectively.

Discussion

An in-depth analysis was conducted concerning the study conducted on snowline elevations and air temperature trends of the Annapurna region between 2000 and 2025. Annual, seasonal, and monthly changes were plotted using various graphs generated by satellite-based datasets. These visualizations are crucial in analysing the kind of changes climate variations have brought upon the elusive Himalayan cryosphere. This section considers findings, interpretations, potential impacts, and previous works on the subject.

From the analysis of annual snowline elevation, a slight positive trend of approximately 0.15 meters per year was observed; however, the very high p-value of 0.9414 indicates statistical insignificance of this trend and, hence, possibly indicates natural variability rather than a definite shift brought upon by climate factors. This result might be seen because of the increased snowfall and precipitation. Besides this, the land topography and climatic variables might cause the downward shift. This, therefore, can be concluded that on an annual scale, the snowline elevation has remained rather unchanged over the course of 25 years, something which can, however, barely be seen on more subtle seasonal and monthly scales.

Contrarily, a clearer pattern emerged in the annual temperature trends (Figure 3). Minimum temperature significantly rose at the rate of 0.08°C per annum, with its p-value significantly supporting the trend (0.0261). Conversely, mean and maximum temperature also tended to lift (with rates of 0.02°C/year and 0.03°C/year) but with respective (non-statistically significant) p-values of 0.3754 and 0.1964. In ascendency, especially with respect to increases in minimum temperature, can very well affect the cryosphere dramatically; reduced refreezing opportunities during warmer nights assist fast snow melts and sustain the melting process.

When considering the annual elevation in snowline and mean temperature (Figure 4), an increasing trend was detected with a slope of 38.46 meters per °C. Yet, with an extremely low value for R^2 (0.10) and a p-value of 0.1165, the temperature-snowline retreat relationship may exist but is also influenced by some other factors, for example, a rainfall pattern, solar radiation, and terrain effects.

Pearson's correlation coefficient' heatmap (Figure 5) offers further proof of the snowline elevation-weather-type connection. The snowline interestingly showed a negative correlation with minimum temperature, -0.34; a small positive correlation with mean temperature, 0.32; and almost zero correlation with maximum temperature, -0.01. In effect, this suggests that snowlines respond more to variations in minimum and average temperatures-where warmer nights and overall energy balance prove detrimental to the melting of snow and ice.

Seasonal snowline elevation trends (Figure 6) gave an even more nuanced view of the phenomena. In summer, the snowline is retreating at an astounding speed, estimated to be -7.47 meters per year, with $p=0.026$ (significant). Hence, a higher summer temperature means more glides and snowmelt. On the contrary, spring, autumn, and winter showed insignificant trends, albeit some alterations.

Making an additional point for the warming scenario is the seasonal temperature trends (Figures 7-9). Minimum temperature rises at 0.06°C per year during winters, but spring and autumn show lesser increases. Very significantly rises the maximum temperature in spring at the rate of 0.03°C per year ($p = 0.00$), while in autumn, it increases at 0.04°C per year to the p-value of 0.010. These values increase the sway temperature changes exerted on seasonal snow dynamics.

Further insights emerge from the scattered plots relating the elevation of seasonal snowlines with mean temperature (Figures 10–13). The winter season shows a relatively strong positive relationship between the snowline and mean temperature with a slope of 73.68 m/°C, an R^2 of 0.53, and a p-value of 0.00, clearly showing that an increase in temperature reflects an upward shift in snowline. Autumn seems to exhibit a similarly strong relationship (slope = 51.39 m/°C, $R^2 = 0.23$, $p = 0.015$). Conversely, spring and summer do not reveal any statistically significant relationships. Spring is almost opposite with no correlation ($R^2 = 0.00$); it may be that precipitation-induced snowfall events in spring override the warming effects.

Despite all these, there exists certain limitations which are undeniable and are mentioned below:

- Spatial resolution of datasets: MODIS (500 m) and ERA5 Land (9 km) resolution limits and data used without bias correction;
- Limited in situ data: Sparse meteorological stations across ACA;
- Cloud detection: Monsoon-driven residual cloud contamination;
- NDSI threshold: Fixed NDSI (>0.4) classification uncertainty.

Conclusion

The study has been conducted in order to know if there was any indication regarding "fading ice" signal which can be connected with changes in temperatures in the region of Annapurna. From the research findings, it is evident that there is a trend of an increased elevation of the snowline at the rate of 0.15 meters annually. This implies that the snowline trends follow environmental factors. While there is an increasing temperature of minimum at the rate of 0.08°C yr^{-1}, mean temperature has an increasing temperature at 0.02°C yr^{-1}, while there is an increase of maximum temperature at 0.03°C yr^{-1} that is not statistically significant. From the yearly snowline-temperature correlation, there is a positive correlation that is still weak considering the sensitivity of 38.46 m/°C, the coefficient of determination of $R^2 = 0.10$, and the strength of correlation gives $r = 0.32$. The seasonal approach reveals more insights. Winter snowline demonstrates high temperature sensitivity with correlation coefficients such as maximum temperature sensitivity (Tmax $r = 0.54$), average temperature sensitivity (Tmean $r = 0.73$), and minimum temperature sensitivity (Tmin $r = 0.70$). It is evident that temperature is the major climatic variable controlling winter season dynamics. Autumn season demonstrates low sensitivity to snowline with sensitivity levels of 51.39 meters per degree Celsius since precipitation and snowfall times are more influential factors.

Overall, it is clear that the elevation of the snowline increases with increasing temperature variance, with minimum temperature being the major climatic factor, and there is a significant variation in this correlation based on the season, especially winter and autumn.

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