Spatiotemporal snowline status and climate variability impact assessment: a case study of Pindari River Basin, Kumaun Himalaya, India

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Abstract

The snowline exhibits significant seasonal shifts upward and downward, reflecting the ever-changing dynamics of the seasons and being influenced by climate variations, which can vary annually. These fluctuations profoundly impact the cryosphere, biota, and ecosystem processes in high mountain regions. Despite the critical role of snowline variations, comprehensive information on how actual climate variability affects snow cover trends in the central mountain range of the western Himalayas is scarce. In the '*Pindari*' region of the Uttarakhand district, India, which is part of the Himalayas, these challenges are exacerbated by the unchecked growth of anthropogenic activities and the broader impacts of climate change. This study analyses snowline variations in the *Pindari* glacial region from 1972 to 2018. The findings revealed that the snowline elevation significantly shifted upward between 1972 and 2018. Notably, this research revealed a decrease in snow-covered areas of approximately 5.01 km^2 over the course of 46 years. This decrease is attributed to a direct response to the increasing number of high-temperature events that occurred during this extended period. This study emphasizes the urgent need for conservation measures in the study region and similar high mountains to combat global warming and safeguard the snowline, which serves as a visible proxy indicator to safeguard high-altitude Himalayan glaciers.

Keywords Snowline, Anthropogenic activities, Climate change, High altitude, Remote sensing, Spectral indices

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Pandey *et al. Environmental Sciences Europe*   (2024) 36:104

Page 2 of 13

Introduction

The snow-capped peaks of the western Himalayas represent sentinels of climate change, and their snowlines trace the delicate balance between areas covered by snow and those that are snow-free slopes and veins. Snow acts as an insulating layer, protecting the underlying glacier ice from direct exposure to warmer air temperatures [45, 52]. When the snowline remains at a higher elevation, glaciers are protected from melting by warmer air temperatures, thus helping to maintain their mass balance [53]. Importantly, the Himalayan glacier is considered the "Water Tower of Asia" because it sources approximately 8.6×106 m^3 of water annually [50]. High mountain regions in the Himalayas, such as the western Himalayas, are characterized by their sensitivity to climatic changes, which manifests as significant alterations in snowline dynamics [35, 60, 65] that negatively impact the glacier systems of the region. Various studies have shown that the northwestern Himalayas have undergone a substantial increase in temperature (1.6 °C) at a proportion more significantly compared with the world mean (global average) over the last era [11, 20, 54]. Moreover, over the western Himalayas, there was a declining trend in snowfall and an increase in temperature [18, 46, 58]. Other studies revealed an increase in temperature in the Himalayas and Tibetans [51], which is much greater than the global average over the last 100 years.

Himalayan glaciers are large masses of ice that formed from the accumulation and compaction of snow over time and face such troubles. The tendency of inclination in snowlines and diminishing snow cover each year influences glacial melt, a phenomenon documented since the 1850s [59, 66, 74]. The evaporation, soil and water also impact on the forest and snow changes in the hilly region [23, 80]. The machine learning and deep learning models have been used for identification of snow and earth features [64, 65, 72]. Outside the polar regions, the Himalayan Mountain range has one of the highest consolidations of glaciers and permanent snow cover fields in the world [29, 33, 76]. Glaciers are essential to humanity because they influence the hydrological cycle at the global level, sustain ocean levels, and provide water to streams continuously [47, 77, 78]. Although the melting of snow and glacial Himalayan cryospheres provide a sufficient water supply for many Himalayan rivers, the flow rate in these rivers has decreased, which could influence water accessibility downstream [29, 34, 75]. Snow and glaciers cover large areas of the Himalayas [10, 28, 32]. These regions are highly vulnerable to climate change. The ice mass available in the Himalayas is approximately 600 billion tons, considered the third-highest on the planet after the northern and southern poles [37]. There has been a 0.74 °C increase in global annual temperature

[16], which significantly negatively impacts high-altitude regions, such as mountains. According to previous studies, since global warming has begun to impact snowmelt and stream runoff in the Himalayan region, it is critical to track snow cover shifts to forecast the future hydrologic cycle. The snowline altitude is an essential parameter for predicting changes in snow cover [3, 40].

The snowline marks the elevation on a mountain where snow persists throughout most, if not all, of the year. The concept of the snowline can involve different temporal and spatial orientations. A shifting snowline represents seasonal patterns in many areas. Climatic variations significantly influence the actual existence of snowlines. The elevation of these rocks can fluctuate annually at the end of the melting period. Remote sensing (such as satellite imagery and aerial photographs) and geographic information systems (computer-based systems) help to measure spatiotemporal snowline shifting. As a result, snowlines have become a significant visible and easily detectable feature in high-elevation hydrological systems [10, 57, 70]. Snow-covered areas typically exhibit higher reflectances in the visible and near-infrared bands than does the underlying terrain. This is because snow reflects a significant amount of sunlight due to its high albedo (reflectivity), while the surrounding terrain absorbs more sunlight [21, 68]. Therefore, identifying the snowline at a given point in time is possible.

The snowline is an important measure of snow depth, and when observed over a wide area, the change in elevation of the snowline suggests a certain climate behavior, either cold or warm. Regularly monitoring snowlines (both spatially and temporally) is essential for assessing hydrological cycle equilibrium and understanding regional and global temperature changes [17, 29, 43, 56].

An increase in the elevation of snowlines is an indicator of climate change because these regions are exposed to the external environment. The accumulation and ablation of snow and ice are affected mainly by temperature and precipitation [2, 7, 24, 46, 63]. The *Pindari* region of Uttarakhand, a region of the Himalayas, is also facing such problems due to haphazardly increasing anthropogenic activities and other human-induced interferences. Changes in climatic conditions are a significant concern for *Pindari* because of its geographical location, which involves both anthropogenic activities and tropical climates and has been affected by climate variations during recent decades.

Glaciers in the *Pindari* area have been found to be shrinking as a result of climatic change and anthropogenic causes. The consistent increase in temperature has led to the quicker melting of glacial reserves in the *Pindari* region. The majority of researchers believe that climate is the primary controlling variable in glacial

Pandey *et al. Environmental Sciences Europe* (2024) 36:104

Page 3 of 13

recessions [30, 61, 69]. Moreover, numerous investigations have distinguished the impact of topography [9, 19]. The warming patterns across the region have quickened the ice mass to dissolve and change the type of precipitation, resulting in a decrease in snow cover and an increase in the height of the snowline.

The recession of Himalayan arc glaciers has affected stream flows and caused the creation of lakes [38, 62, 79], which may be possible sites for glacial lake outbursts resulting from floods. This cryosphere region in Uttarakhand is retreating at an accelerated pace compared to that in other high-mountain Asia regions. Glacier depletion in the *Pindari* Valley is an example of glacial depletion in the Uttarakhand Mountains [8, 47]. The land framework changes in the locale have been connected to exhausting stream flows, financial contemplations, and spontaneous land change. Changes in the snowline pattern in the study area will have long-term socioeconomic and environmental implications for agriculture, land management, water-based ventures, climate, water supplies, and numerous other development exercises. Hence, this study aimed to (1) assess the long-term trends in snowline elevation and snow cover extent in the Pindari glacial region of the western Himalayas from 1972 to 2018 and (2) investigate the relationship between high-temperature events and the observed upward shift in snowline elevation and decrease in snow cover. This study lays the preliminary groundwork for establishing a database that tracks temporal changes in the snowline within the *Pindari* region, focusing on how these changes are linked to increasing temperatures due to climate variabilities. Additionally, this research serves as a proxy for exploring the impact of temperature fluctuations on the rate at which snow melts in the western Himalayas, using this region as a representative area.

Study area

Uttarakhand, one of India's northern states, belongs to the region of the Western Himalayas. The Himalayan region of Uttarakhand State of India encompasses a 320 km stretch of mountain ranges between the *Kali* River, which forms the border between India and Nepal in the eastern part of the Pithoragarh district of Uttarakhand, and the valleys of Tones-Pabar, which form Himachal Pradesh's eastern border.

The study addresses the Pinder watershed (Kumaun Himalaya) (Fig. 1), which extends between 30° 6.25' N and 30° 19.25' N and between 79° 47.95' E and 80° 5.69' E and encompasses an area of 391.05 km². The *Pindari* Glacier region is a center in the study area located close to Chhanguch Glacier, which is part of the Upper Himalayan range in the northern part of Uttarakhand State, India. The Pindar River is the largest of the Ganga

River's branches. Its current origin location is 3,847 m at 30°16.47′ N and 80°00.48′ E. The study site experienced various climatic circumstances ranging from heavy to sunny snowfall and needed a 70 km hike from the village *'Song'* [47]. The average summer temperature in the area is between -10 °C and -15 °C, and the average winter temperature is between -20 °C and -40 °C. The quickest path to Milam Glacier is by the tongue of *Pindari* Glacier, which is referred to as the 'Trail Pass'. *Changuch* (6322 m asl), *Nandakhat* (6611 m asl), *Nandakot* (6860 m asl), *Pawalidwar* (6663 m asl), and *Baljuri* (5922 m asl) are the peaks near the *Pindari* glacier regions. The rationale for selecting the *Pindari* region as the study site included three key factors: (1) its clear visibility on satellite imagery, (2) minimal cloud cover, and (3) the presence of climate change impacts, such as a sustained rise in temperatures and human-induced activities leading to the rapid melting of glacial reserves in the *Pindari* region [8, 47].

Methodology
Dataset and methods

To differentiate between snow cover and adjacent bare rocks, temporal satellite images were categorized into these two classes, and then, snowline changes were analyzed; for this purpose, we used Landsat Series Data-1–3 MSS (1972), 4–5 TM (1980), 4–5 TM (1993), ETM-7 (1999), 4–5 TM (2011), and Sentinel 2 MSI (2018) **(**Supplementary Table S1–S6). An accuracy assessment (Supplementary Table S7) was performed to validate the accuracy of the classified maps. Ground truth points (i.e., snow and nonsnow areas) that were gathered from field observations and high-resolution Google Earth images were used to measure accuracy. The overall accuracy of the classified maps was calculated (formula) to determine the accuracy of the output maps:

$$\frac{\text{Correctly classified point}}{\text{Total collected points}} * 100$$

Landsat series data and Sentinel-2 data are freely available on the official websites of https://www.usgs.gov/. The Top of the Atmospheric Reflectance (ToA) was calculated to correct Landsat image errors caused by upper atmospheric constituents [48]. Finally, the subset images of all the years were classified to delineate the snowline from adjoining bare rocks of the *Pindari* region.

The snowlines were measured using an on-screen visual analysis technique with temporal satellite datasets. We compared the snowlines of different time periods in the region and inferred the retreat rate over the last 46 years, spanning between 1972 and 2018. We used different satellite data (07 years) from four decades
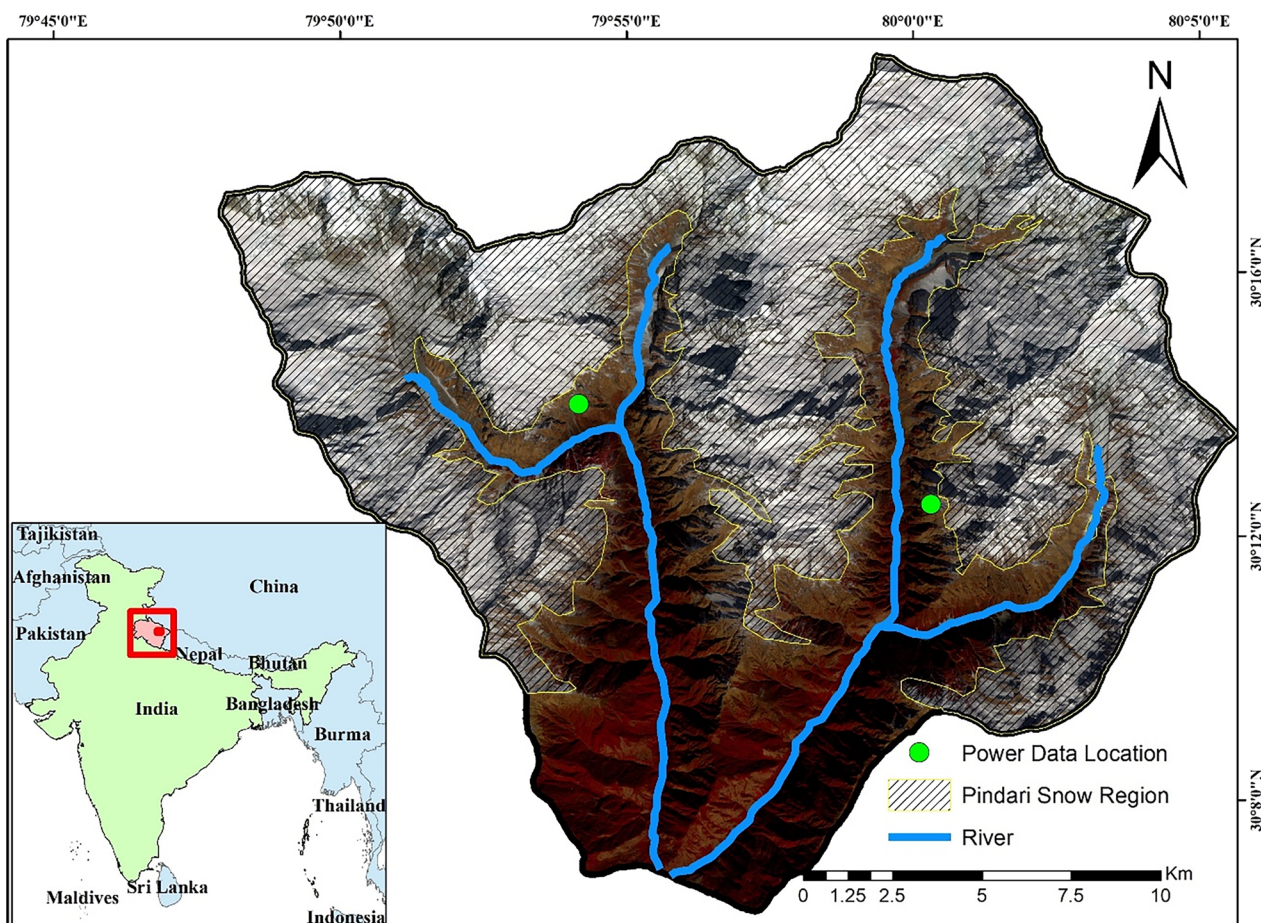
Pandey *et al. Environmental Sciences Europe*   (2024) 36:104

Page 4 of 13

Fig. 1 Study area in the *Pindari* Valley region in the Kumaun Himalaya region of Uttarakhand, India

(46 years) to detect snowline shifting patterns, as satellite data facilitate overcoming spatial and temporal scaling problems that plague simulation and experiment-based yield gap studies [5]. Satellite data can distinguisogical features in particular areas and are now more accessible and inexpensive than ever.

The overall method adopted for conducting the study is presented in Fig. 2. The study starts by collecting the dataset for the analysis section. All the datasets were collected from the USGC official web portal "https://www.usgs.gov/", and the full description of the data used and methodology used are shown below.

Meteorological datasets (*power data access viewer)*
We used observed meteorological data from NASA's online web portal of power data access viewer in our study methodology for comparing our results with temperature fluctuations. We downloaded the temperature dataset from 1981 to 2018. The power data access viewer provides different meteorological datasets in the form of text, geospatial datasets, and files, which can be downloaded from users and integrated into different supporting software for further application, analysis, and visualization; the data provided by the access viewer have a resolution of 0.25×0.25 degrees (https://power.larc.nasa.gov/docs/tutorials/data-access-viewer/userguide/#introduction). We downloaded the temperature data using the regional data access widget provided by the portal, from which we constructed a rectangular study area. We obtained two sets of coordinate data: 30° 15' N–79° 45' E and 30° 15' N–80° 15' E. Then, we formatted the data in different months from 1981 to 2018 to show the trends of the mean monthly minimum and maximum temperatures at the location of the study area.

Preprocessing of Landsat data
After the datasets are retrieved, the images contain two main types of errors: "Radiometric" and "Geometric". This study rectified the radiometric errors (radiometric correction) and found the right quality image; we included the ToA operation using Eq. (1) on every temporal satellite image. ToA reflectance and the data were
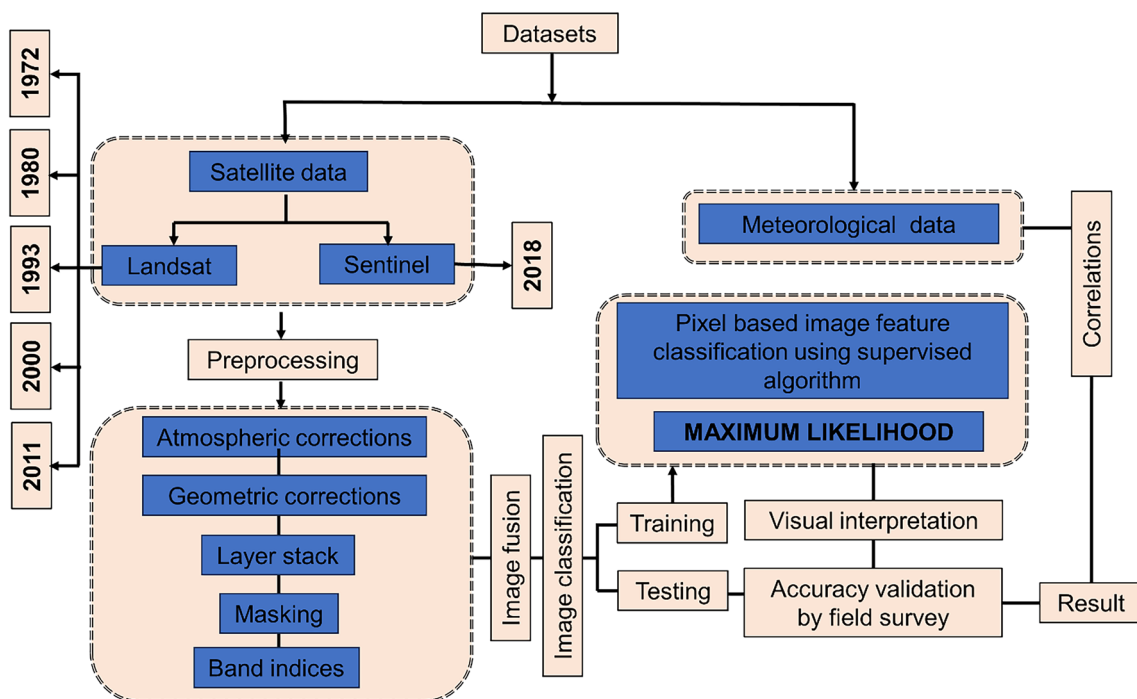
Pandey *et al. Environmental Sciences Europe*   (2024) 36:104

Page 5 of 13

Fig. 2 Overall methodological framework for conducting the study

converted into 16 unsigned bits to obtain the same data from the USGS.

Top-of-atmosphere (ToA) corrections

The top-of-atmosphere reflectance is the value detected by space-based equipment as it travels above the Earth's atmosphere. The reflectance values are influenced by clouds, aerosols, and atmospheric compounds. The reflectance is converted using the TOA operation, which can be derived using Eq. (1):

$$\rho_\lambda = \frac{\pi * L_\lambda * d^2}{ESUN_\lambda * cos\theta_s} \tag{1}$$

where d = Earth–Sun distance in astronomical units,ρ_λ = planetary reflectance measurements,L_λ = spectral radiance,θ_s = solar zenith angle, and $ESUN_\lambda$ = mean solar exo-atmospheric irradiance.

Geometric corrections (GC) and image processing

The operation of geometric correction (GC) follows after performing the ToA. The GC process was performed using a toposheet obtained from the official web portal of the survey department of India (scale = 1:50,000). We used the nearest neighbor sampling approach to geometrically adjust the satellite photos. All the required satellite images (Landsat MSS, TM, ETM+, and Sentinel 2A) were rectified geometrically by using a root

mean square error (RMSE) < 0.6 pixels. Layer stacking in ERDAS Imagine combines corrected bands into a unified band for analysis, enabling diverse band combinations for improved ground cover visualization. Subsequently, images were mosaicked into a composite and subsetted using the study area. In the realm of image processing, after initial preprocessing, we conducted image fusion to obtain a high-resolution image suitable for object detection in satellite imagery. This fusion technique enhanced the resolution of the 1999 Landsat 7 ETM+ image, aiding in identifying features such as the snowline and vegetation line through visual interpretation. Image fusion involves combining data from multiple satellite image bands into a single composite, yielding imagery with enhanced spectral and spatial resolution. In our research, we utilized Landsat 7 ETM+ images alongside panchromatic and multispectral data processed using ERDAS Imagine software with the nearest neighbor sampling method to ensure accurate fusion.

Image classification

The classification operation generates the output in which the pixels of a satellite image are categorized into various feature classes of land cover. These output classified data are then further used to prepare different theme-based (thematic) land use/land cover maps. There are currently two types of classification methods: supervised and unsupervised. Here, in the present study, we

Pandey *et al. Environmental Sciences Europe*   (2024) 36:104

Page 6 of 13

include the supervised and spectral indices of the NDSI given in Eq. (2) for classifying snow cover and finding snowlines. The main objective of classifying satellite imagery is to generate valuable information from the raw data acquired by the satellite in digital numbers:

$$NDSI = \frac{Band_{Green} - Band_{NIR}}{Band_{Green-NIR}}.$$ (2)

The supervised classification method is one of the most widely used classification methods in remote sensing science [39]. The user sets a well-defined signature or training set to prepare a supervised classifier model. The main difference between supervised and unsupervised methods is the control of the classifier model [49]. In a supervised classifier, the total control of the model depends on the user, but in the case of the unsupervised classifier method, the control depends on computer-defined parameters. Once each information class has been statistically characterized, the image is identified by analyzing each pixel's reflectance and deciding on the most similar reflectance spectral signatures. This study included the supervised classifier "maximum likelihood". The maximum likelihood (ML) decision criterion is a statistical function used to assign pixels for a given class with the highest chance of improving the classification of overlapping signatures. The ML classifier uses the Bayesian equation to compute the weighted distance or probability (D) of a nondefined measurement of vector (X), which refers to one of the defined function classes of (Mc), and (T) signifies the transposition function as given in Eq. (3) [15]. It is a parametric classifier algorithm that assumes that the digital number of the satellite image has a Gaussian distribution of the classes represented in the image:

$$\begin{aligned} D = &ln(a_c) - [0.5ln(|COV_c|)] \\ &- [0.5(X - Mc)T(COV_c - 1)(X - Mc)]. \end{aligned}$$ (3)

Visual interpretation

The snowline locations were physically translated and digitized as polygon files using the ArcGIS v.9.3 platform each year, and the area of each polygon was calculated. The results were finally compared using Microsoft Excel 2013. After validating the satisfactory results, we generated a layout map of the 1972, 1980, 1993, 1999, 2011, and 2018 study periods.

Relation between temperature fluctuations and snowline shift

GPS coordinates for snowlines at 30-m intervals from different years were collected using ArcGIS 10.3. Elevation data from ASTER imagery were then extracted to create an elevation dataset for the years 1972, 1980, 1993,

1999, 2011, and 2018. Next, the average elevation for each snowline was calculated, and ANOVA was performed to assess the patterns in the mean elevational shifts across various years. Additionally, we compared the differences in mean snowline elevations between 1972 and 2018. Furthermore, we compared the mean monthly minimum and maximum temperatures from 1981 to 2018 and conducted an ANOVA to assess whether there was a significant change in these temperatures across the same period. Finally, we examined the trends in snowline shifts in relation to the monthly minimum and maximum temperatures throughout the study period.

Results

The current study examines the effect of environmental temperature variabilities on Himalayan snow cover, mainly in the upper *Pindari* region of Uttarakhand, using Sentinel 2A and Landsat time-series data with multispectral performance change detection analysis for identifying changes in land use/land cover resources using geo-corrected remotely sensed data. In this study, changes in snowlines in response to temperature increases and temporal changes were the primary concern.

This work depicts the change in the *Pindari* region's snowline location from 1972 to 2018 with the help of multiresolution satellite imagery for the years 1972, 1980, 1993, 1999, 2011, and 2018 (Fig. 3). The mean elevational shifts within the snowlines during these years are shown in boxplots (Fig. 4).

The ANOVA test suggested that there were statistically significant differences in snow line elevations across the different years ($F = 930.6$, $p < 0.05$). The Welch two-sample t-test indicated a highly significant difference in elevation means between 2018 and 1972, with the mean elevation (within the snow line) in 2018 being significantly greater than that in 1972 ($t = 50.174$, $df = 8473.8$, $p < 0.05$).

Between 1972 and 2018, there was a minimum elevation change of 63 m from the lower side, with an average annual upward shift of 1.36 m. Additionally, a maximum elevation change of 77 m was observed, with an average annual upward shift of 1.67 m; all image accuracy values ranged between 91.59 and 87.27 (Supplementary Table S7). Tables 1 and 2 show the snowline shifts for both the maximum and minimum elevation changes during the study years. The snowline represents the elevation above which snow remains year-round, and its movement is influenced primarily by climate variations, especially environmental temperature fluctuations, both upward and downward. However, the snow cover area also decreased by 5.01 km^2 in the span of 46 years, which represents a retreat rate of 0.108/year (Tables 1 and 2).
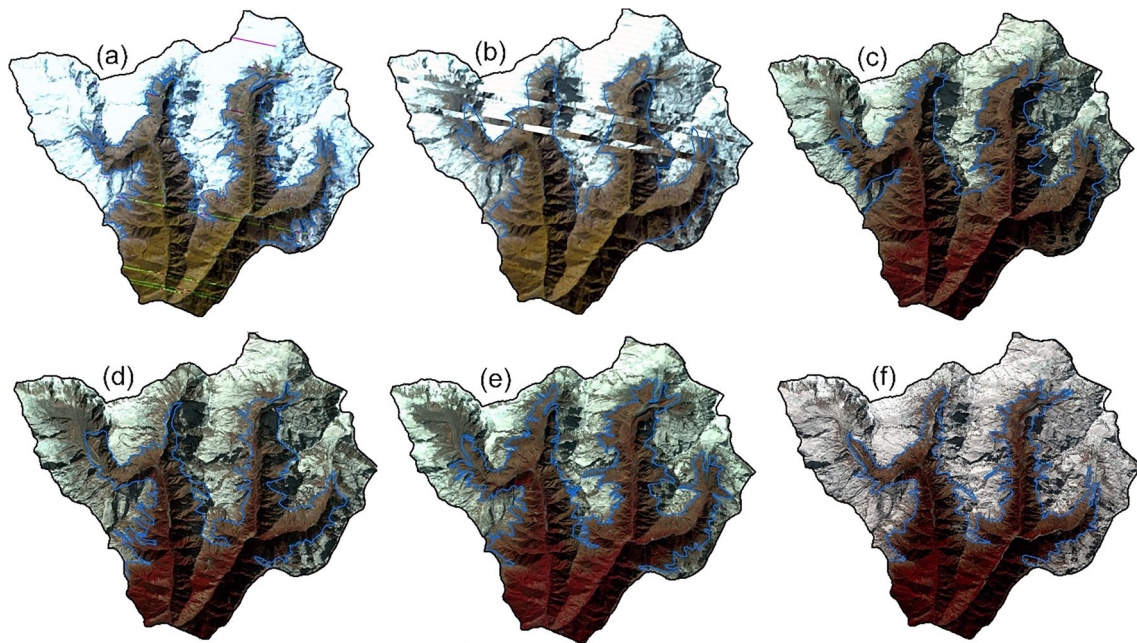
Fig. 3 Snowlines (blue lines) derived from the satellite image classification for **a** 1972, **b** 1980, **c** 1993, **d** 1999, **d** 2011, and **f** 2018
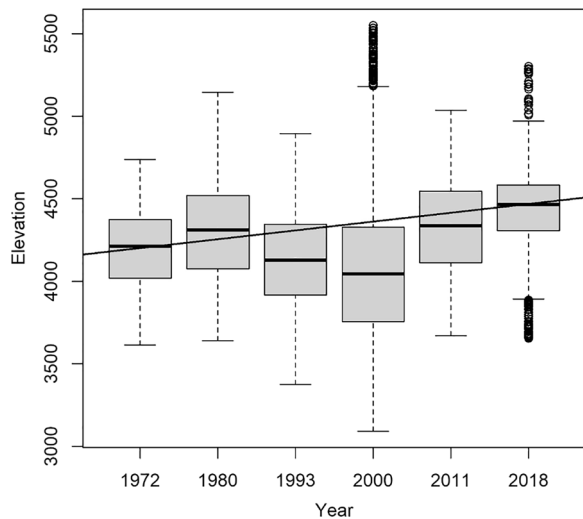

Fig. 4 Distributions of elevation across the snowlines in different study years with the mean elevation for each year. The trend line shows that the mean elevation shifted from 1972 to 2018

Table 1 Minimum and maximum snow line variations and snow cover in the *Pindari* Valley from 1972 to 2018

S. no	Year	Elevations of snow line (m)		Snow cover area (km^2)
		Minimum	**Maximum**	
1	1972	2560	2571	216.03
2	1980	2588	2605	213.65
3	1993	2896	2903	213.77
4	1999	2652	2685	209.54
5	2011	2786	2812	205.10
6	2018	2623	2648	211.02

Table 2 The net changes in snow line and snow cover in the *Pindari* valley of Uttarakhand from 1972–2018

Time period	Elevation change (m)		change in Snow cover (km^2)
	Minimum	**Maximum**	
Change from 1972 to 1980	028 ↑	034 ↑	2.38 ↓
Change from 1980 to 1993	308 ↑	298 ↑	0.12 ↑
Change from 1993 to 1999	244 ↓	218 ↓	4.23 ↓
Change from 1999 to 2011	134 ↑	127 ↑	4.44 ↓
Change from 2011 to 2018	163 ↓	164 ↓	5.92 ↑
Overall change from 1972 to 2018	063 ↑	077 ↑	5.01 ↓

A graphical representation (Fig. 5a, b) shows the overall maximum and minimum monthly temperature variations from 1981 to 2018. The seasonal temperature data reveal a consistent upward trend in the monthly minimum temperature across the years 1981 to 2018, as depicted in Fig. 6a–c. Conversely, the monthly maximum temperatures exhibit a slight
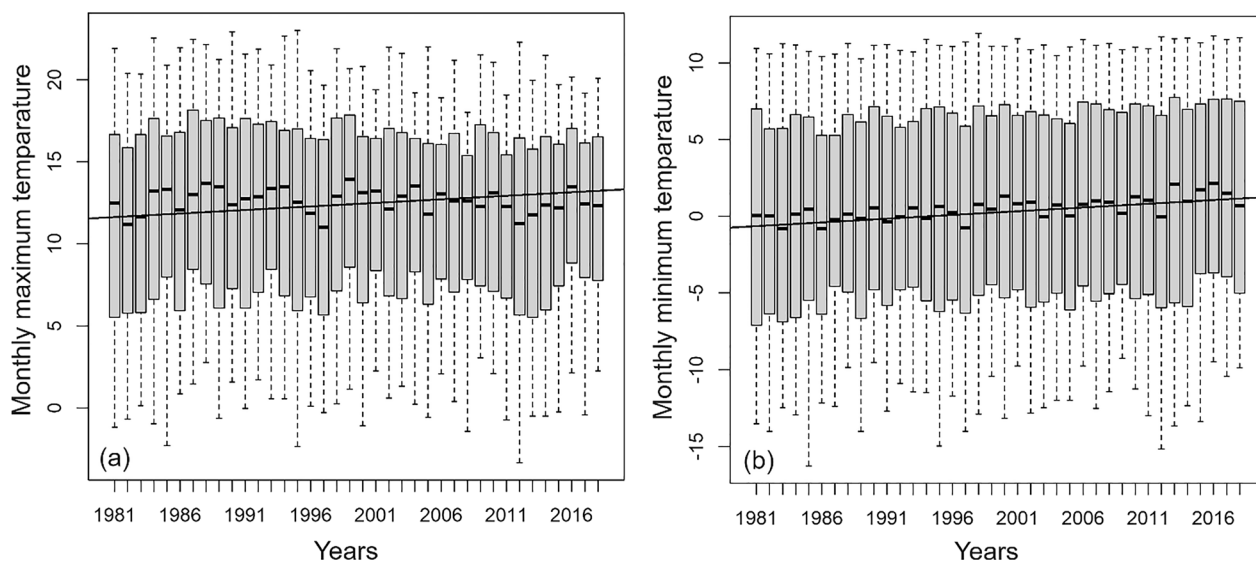
Fig. 5 The graphical depiction displays the fluctuations in monthly temperature, highlighting both the maximum and minimum temperatures from 1981 to 2018. Additionally, the overall trend of temperature increase over time was illustrated

decline for all seasons during the same period, as illustrated in Fig. 6d–f.

Discussion

Spatiotemporal shifts in the snowline

The observed changes in snowline locations from 1972 to 2018 present a compelling narrative of the region's response to temperature increases and temporal variations. The snowline, which represents the elevation above which snow persists throughout the year, is a sensitive indicator of climatic variations. The mean elevational shift within snowlines across these years, as depicted in Fig. 4, highlights a clear upward trend in snowline elevation.

As indicated by the ANOVA test, the statistically significant differences in snowline elevations reaffirmed the ongoing changes in the region's snow cover. The Welch two-sample t-test further revealed that these changes were particularly pronounced between 2018 and 1972, with the mean elevation in 2018 being significantly greater than that in 1972. The magnitude of these elevational shifts is noteworthy, with a minimum upward change of 63 m and a maximum change of 77 m occurring between 1972 and 2018. This translates to an average annual upward shift of 1.36 m to 1.67 m. These findings align with regional studies in the Himalayas [14, 64] and reflect a broader trend of elevational shifts in response to warming temperatures.

Snow cover area and retreat rate

Beyond the changes in snowline elevation, the reduction in snow cover area emerges as a notable and concerning outcome of this comprehensive study. Over a 46-year period, the Pindari region experienced a substantial decrease in snow cover area, amounting to 5.01 km^2, equivalent to a retreat rate of 0.108 km^2 per year. This decrease in snow cover area mirrors broader global trends observed in mountainous regions [27, 55] and underscores the heightened vulnerability of high mountain regions to the impacts of climate change.

The retreat rate observed in this study aligns with findings from extensive research conducted in the Himalayas [4, 44], further emphasizing the region's acute sensitivity to rising temperatures and the broader implications of climate change on mountain ecosystems and downstream communities. This reduction in snow cover area has complex consequences, affecting not only the availability of water resources, but also the livelihoods and biodiversity of the region.

The findings presented here align with a growing body of research highlighting the intricate relationship between climate change and the cryosphere in high mountain regions. The observed retreat of the Pindari region's snow cover area indicates that larger changes occurred in mountainous areas across the globe. As the snow cover continues to diminish, it is imperative to develop and implement climate-resilient strategies to address the challenges associated with reduced water resources, potential water-related hazards, and the need
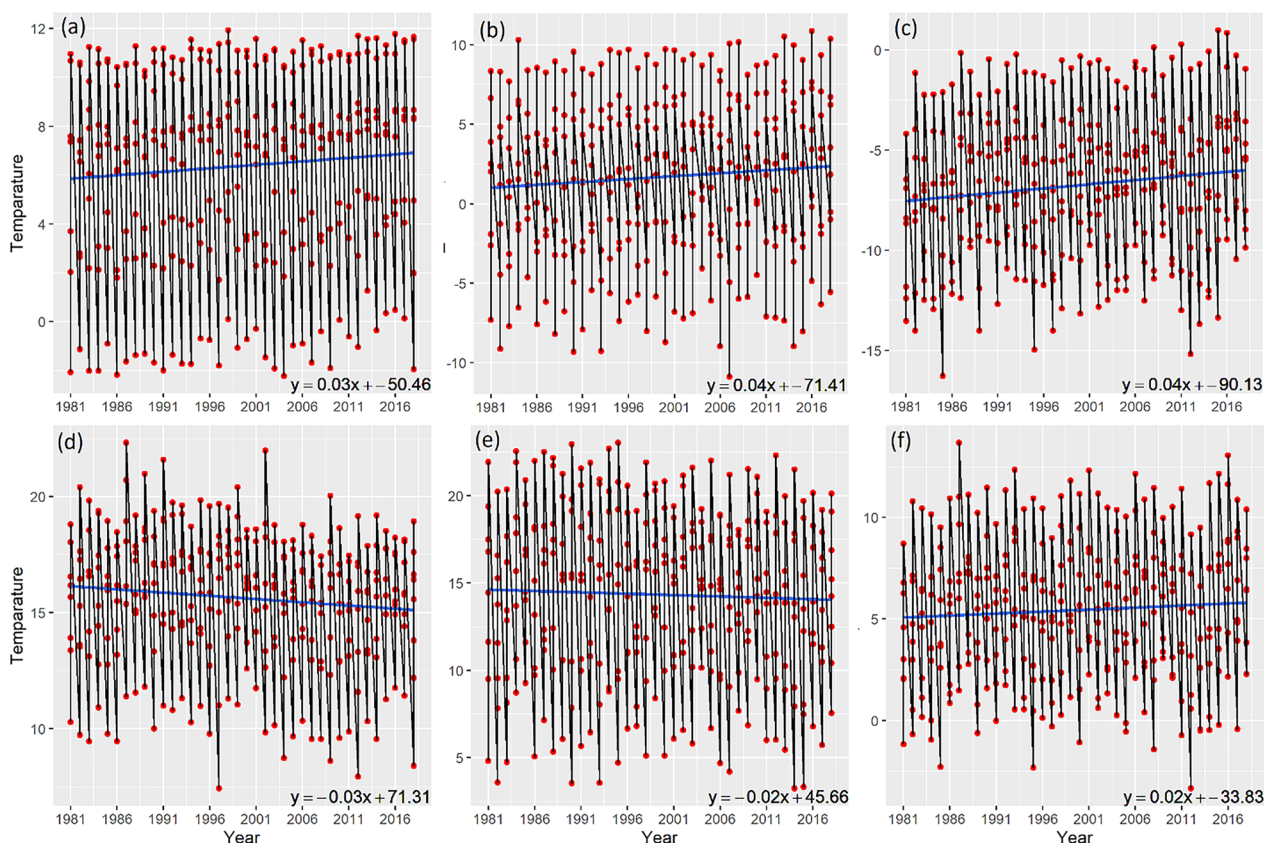
Fig. 6 Seasonwise minimum monthly temperature trends in **a** monsoon season, **b** summer, and **c** winter, whereas seasonwise maximum monthly temperature trends in **d** monsoon season, **e** summer, and **f** winter in the Pindari region of Uttarakhand, India (1981–2020)

for adaptation and mitigation measures to safeguard mountain regions' ecological and societal stability.

Temperature trends

The analysis of temperature trends plays a pivotal role in framing the observed alterations in snowline positions and snow cover areas. The consistent and discernible upward trajectory in monthly minimum temperatures spanning from 1981 to 2018 is a compelling indicator of a pronounced warming trend in the Pindari region. This warming trend aligns with overarching global climate change patterns and resonates with research findings from the Himalayan region, which have led to the amplification of warming trends [1, 26, 36].

The counterintuitive decrease in monthly maximum temperatures during the same period is emblematic of a complex climatic phenomenon noted in various mountainous areas [41]. This phenomenon is attributed to a combination of factors, including shifts in cloud cover patterns, alterations in precipitation regimes, and the influence of the snow–albedo feedback effect on temperature dynamics. The interaction among these intricate factors leads to a noticeable decrease in daytime temperatures, even as minimum temperatures continue to rise in the background. These nuanced temperature dynamics underscore the intricate nature of climate change in high mountain regions and necessitate a comprehensive understanding of the multifaceted factors contributing to the observed trends.

These findings highlight the critical role of local climate drivers in shaping temperature patterns in mountainous regions, where changes in temperature dynamics may have cascading effects on snow cover, the mass balance of glaciers, hydrology, and local ecosystems. The observed temperature trends serve as an essential backdrop for interpreting shifts in the cryosphere, emphasizing the urgency of continued research and adaptive strategies for these vulnerable regions.

Comparison with global and regional studies

These findings concur with the broader global and regional trends concerning shifts in snow cover and temperature dynamics. At the global scale, extensive research has consistently reported a reduction in both the extent and duration of snow cover [13, 42], indicating a response to the pervasive influence of climate change.

Pandey *et al. Environmental Sciences Europe*   (2024) 36:104

Page 10 of 13

The Himalayan region, known for its complex topography and ecological significance, has been a focal point for in-depth investigations. Research carried out in the Himalayas has consistently noted the retreat of glaciers and variations in the amount of snow cover, indicating the increasing influence of increasing temperatures and changing patterns of precipitation [6, 12].

Delving into the specific context of the Kumaun Himalaya, the findings of this study resonate with observations made in neighboring regions. Notably, in Himachal Pradesh [22, 25] and Nepal [31, 67], similar shifts in snowline positions and a decrease in snow cover have been attributed to the pronounced influence of rising temperatures and alterations in precipitation regimes. Notably, these regional trends transcend the boundaries of the mountainous areas themselves. The consequences of these disasters ripple downstream, profoundly affecting the availability of freshwater resources, the integrity of fragile ecosystems, and the livelihoods of communities that are intricately tied to these resources for their sustenance [70].

This collective body of evidence underscores the imperative of addressing climate change and its multilayered impacts on high mountain regions. Given their pivotal role as water towers, providing essential freshwater resources for vast populations and supporting unique ecosystems, comprehending the underlying mechanisms governing snow cover and temperature variations is imperative. Such an understanding is critical for the development of adaptive strategies and the formulation of well-informed policies to mitigate the far-reaching consequences of climate change in these sensitive environments.

Conclusion

The spatiotemporal mapping of snow cover and snowlines through remotely sensed satellite imagery from different years plays a vital role in high-elevation ecological protection and conservation. This study revealed that in 1972, 1980, 1993, 1999, 2011, and 2018, the snow cover decreased to 5.01 km^2, equivalent to a retreat rate of 0.108 km^2/year, and a significant shift in the minimum and maximum snowline elevation occurred. The main cause of this snowline shift and decrease in the field of snow cover in the region is an increase in temperature. These changes have dramatic impacts on the ecology and environment of the Himalayas. The results of this study on the impact of environmental temperature variabilities on Himalayan snow cover, particularly in the upper Pindari region of Uttarakhand, have several significant implications for mitigation strategies and provide valuable suggestions for policymakers. The findings from this preliminary case study serve as concrete evidence of the ongoing impact of climate change on the Himalayan region. This finding reinforces the importance of raising awareness about climate change and its effects on local environments. Policymakers can use this information to advocate for climate action and communicate the urgency of mitigating climate change to the public.

The observed decreases in snow cover area and shifting snowlines indicate a direct consequence of rising temperatures. Policymakers should take these findings into account when developing mitigation strategies, such as reducing greenhouse gas emissions and transitioning to sustainable energy sources. Implementing mitigation measures can help slow or even reverse these negative trends. Understanding the trends in temperature and snow cover is essential for planning adaptation measures in the Himalayan region. Policymakers should invest in infrastructure and policies addressing water resource management, disaster preparedness, and sustainable agricultural practices to help communities adapt to changing conditions. Given the region's significance in terms of tourism and its economic role, declining snow cover can adversely affect the local economy, necessitating diversification and alternative opportunities for stability. Furthermore, the cross-border nature of the Himalayan region offers a unique opportunity for policymakers to foster international collaboration on climate and environmental issues, recognizing the importance of regional cooperation in effectively addressing transboundary challenges. Changes in snow cover and temperature have implications for public health and safety, affecting the availability of water resources and the risk of natural disasters. Policymakers must prioritize the well-being of the local population and develop strategies to mitigate these risks. To stay informed and adapt policies accordingly, continued monitoring of temperature, snow cover, and land use is crucial, as it requires support for ongoing research and data collection efforts.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12302-024-00924-7.

Supplementary Material 1: Table S1. Landsat 1 satellite and characteristics. Details of acquiring dates and resolution of the imageries used to study Kafni, Sundardhunga, Baljuri Base Camp glacier. Table S2. Details of Acquiring Year and resolution of the imageries used for the study of *Pindari* Glacier. Table S3. Metadata of Landsat MSS. Table S4. Metadata of Landsat 4 and 5 TM. Table S5. Metadata of Landsat 7 ETM$^+$. Table S6. Metadata of sentinel 2 dataset. Table S7. Accuracy assessment of study area in the different year.

Pandey *et al. Environmental Sciences Europe*   (2024) 36:104

Page 11 of 13

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Author contributions

All the authors contributed equally to the conceptualization, methodology development, data collection, investigation and modeling, original draft preparation, writing and editing. The authors certify that there is no conflicts of interest. Arvind Pandey: conceptualization, methodology, investigation, data collection, data interpretation, analysis, software guidance, original draft preparation, writing and editing. Deepanshu Parashar: conceptualization, methodology, data collection, data interpretation, investigation and modeling, analysis, writing and editing. Sarita Palni: conceptualization, methodology, data collection, investigation and modeling, software, writing and editing. Mriganka Shekhar Sarkar: conceptualization, methodology, investigation, writing and editing. Arun Pratap Mishra: methodology, investigation, original draft preparation, revision, review, writing and editing. Ajit Pratap Singh: investigation, conceptualization, visualization, modeling and analysis, writing and editing, overall supervision and guidance. Romulus Costache: original draft writing, review, writing and editing. Tuhami Jamil Abdulqadim: review, original draft, writing and editing. Chaitanya B. Pande: investigation, original draft, review, writing and editing. Abebe Debele Tolche: original draft, review, writing and editing. Mohd Yawar Ali: formal analysis, review, writing and editing.

Availability of data

The data that support the findings of this study are available upon request from the corresponding author.

Declarations

Competing interests

The authors have no conflicts of interest to declare.

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Pandey *et al. Environmental Sciences Europe*   (2024) 36:104

Page 12 of 13

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Page 13 of 13

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