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Snow Cover and Snowline Altitude Variations in Alaknanda Basin, Uttarakhand, Central Himalayas

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Abstract: ***Snow is an important component of the cryosphere and the study of snow is essential for understanding regional climate change and managing water resources. Numerous studies suggest that global warming has started affecting snow melt and stream run-off in the Himalayan region. Monitoring the snow-cover changes is therefore essential to assess the future hydrological cycle. Snowline altitude is an important parameter to assess future changes in snow cover. Variations in snowline altitude (1976-2010) and snow cover for the years 2000 to 2013 in Alaknanda River Basin located in Uttarakhand are reported here. Snow cover mapping in Alaknanda Basin is accomplished from 2000 to 2012 by generating snow cover area (SCA) from Moderate-Resolution Imaging Spectroradiometer of 500 meters (MYD10A1-Binary), which shows a slight declining trend during 2000-2012. The average snowline was delineated using Landsat (30 meters) images of November 1976, 1990, 1998 and 2010 using digital identification method and elevation information generated using SRTM data. The lowest snowline altitude was observed as 4287.88 m in November 1998 and highest as 5063.66 m in November 1976.***

Keywords: Snow-covered area, Modis-Binary Product, Snowline, Digital Extraction, SRTM.

1. Introduction

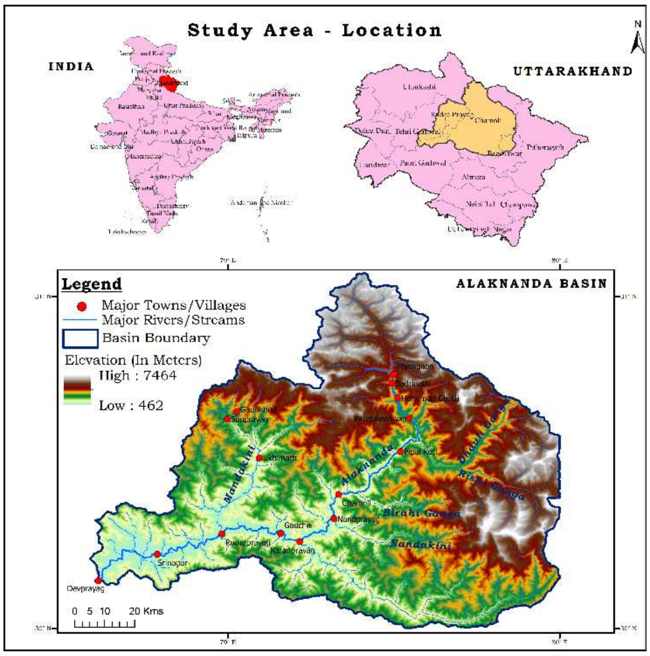
Snow is one of the most sensitive and vital natural resources, and studying its trends is very essential for understanding regional climate variations. The Himalaya has one of the largest concentrations of snow and ice outside the Polar Regions. Changes in the snow budget in this region will have long-term socioeconomic and environmental implications for agriculture, water-based industries, environment, land management, water supplies, and many other development activities [1]. Ice cover is decreasing in this region, as for most glaciers in the world. The glaciers in Himalayan region are losing an average 0.4% area per year. This is general tendency and loss in area is different in different parts of Himalayan region2. Between 2003 and 2009, Himalayan glaciers lost an estimated 174 gigatonnes of water, and contributed to catastrophic floods in the Indus, Ganges and Brahmaputra rivers [2]. Himalayan glaciers form the focus of majority of public and scientific debate. A poor understanding of the processes affecting them, combined with the diversity of climatic conditions and the extremes of topographical relief within the region, make projections speculative. Prevailing uncertainties are of major concern because some future projections regarding snow cover have serious implications for water resources.

The importance of accurate snow-cover-extent is immense due to existing feedback between snow cover, temperature and albedo. Typical albedo values for non-melting snow-covered surfaces are very high (80-90%). Higher global temperatures lead to larger snowmelt and less snowfall, which in turn decreases surface albedo. As a result, there is an increase in solar radiation absorption which further increases global temperatures. Thus, snow-covered surfaces have an essential cooling function for the whole region. The snow line is an important indicator of snow coverage. Its spatial fluctuation reflects climatic behavior, indicating a tendency either towards cold and/or wet conditions or towards a warmer climate. Inaccurate snow-cover extent estimation may lead to erroneous climatic conclusions which in turn may mislead decision makers and citizens and might lead to adverse social effects. Therefore, mapping areal extent of snow and its average altitude form an important parameter for various hydrological, climatological, and snow-hazard applications. Hence an attempt has been made in this study to map the snow cover and average snowline altitude in Alaknanda Basin using multi-sensor, multi-temporal images of Landsat and MODIS.

Remote sensing has served as an efficient method of gathering data about glaciated areas since its emergence. Owing to their synoptic view, repetitive coverage and up-to-datedness, remote sensing materials are an unprecedentedly powerful and efficient tool to study glaciers that are usually located in remote, inaccessible and inhospitable environments. Recently, remote sensing data has been frequently used in generating quick and reliable information on glaciers. Numerous studies have been performed on the mapping of seasonal snow cover using different methods and optical sensors globally by Dozier [3, 4, 5]; Hall [6, 7,]; Klein [8]; Vikhamaret[9];Salomonson and Appel [10]; Painter [11]. In addition, many studies have been conducted on snow cover mapping in Himalaya using optical satellite sensors by Gupta [12]; Kulkarni [13, 14, 15]; Jain [16];Negi[17]; Immerzeel [18].

2. Study Area and Data Used

Alaknanda basin lies in the north eastern part of Uttarakhand state (Fig. 1). The Alaknanda basin is characterized by hilly terrain, deep gorges, and river valleys. It is also the source of a major river of India, i.e. the Alaknanda River. The basin has 407 glaciers covering an area of 860 km^2 and volume of around 90.7 km^3. The major portion of the Alaknanda basin falls in Chamoli district. Since, the area has perennial water resources, it provides ideal sites for many micro-hydropower projects. This study uses MODIS snow product, namely; Binary snow cover product from 2000 to 2012 to assess snow cover trends and its variations with respect to elevation and aspect. Multi-temporal Landsat images of November 1976, 1990, 1998, 2010 along with SRTM data are used for estimating average snowline altitude for Alaknanda basin.



3. Snow Cover Area

A snow cover is formed by deposition of snow on the ground surface. The term areal extent of snow cover may be defined as the extent of ground area covered by snow irrespective of its depth and water equivalent. In warm conditions, the snow may melt away just after its fall or stay for a short period. Snow cover that stays only for a few days and then depletes away due to climatic conditions is known as temporary snow cover. The snow cover accumulated during accumulation period called as seasonal snow cover area, melts away during the next summer season. Depletion curves of snow covered areas continuously indicate the gradual areal reduction of the seasonal snow cover during the snowmelt season. The snow cover depletion curves normally relate the areal extent of the snow cover over a period of time. The different kinds of data may be used to compile the snow depletion curve viz. ground observations, aircraft photography, and satellite imagery. Satellite imageries are being used successfully to obtain snow-cover area data in near-real time for year-round monitoring and studies over vast, rugged and remote areas, since it is easiest to analyze and that too quite accurately. Snow cover mapping in Alaknanda basin was accomplished using MODIS (Moderate-Resolution Imaging Spectroradiometer) Binary snow product (MOD10A1/MYD10A1). The MODIS snow product is available at 500 m spatial resolution.

MODIS ''binary'' (i.e., snow or not-snow) snow cover is based on the normalized difference snow index originally developed for Landsat (Dozier, 1989), available from Terra (product MOD10A1) since 2000 and from Aqua (product MYD10A1) since 2002 (Hall et al 2002). Remote sensing investigations were first used to contrast in the reflectance of snow between the visible spectrum, where snow is bright, and the shortwave infrared spectrum, where snow is dark, to discriminate clouds from snow [19, 20]. The normalized difference snow index [5] applies this contrast to discriminate snow from clouds and other surface covers in mountainous terrain, where the local solar illumination angle varies pixel-by-pixel. The MOD10A1/MYD10A1 products are based on this normalized difference (NDSI):

$$NDSI = \frac{R_{VIS} - R_{SWIR}}{R_{VIS} - R_{SWIR}} \quad (1)$$

R represents planetary spectral reflectance in a visible band and a shortwave infrared band. For the MODIS snow products [7], these are Terra MODIS bands 4 (0.545–0.565 μm) and 6 (1.628–1.652 μm). On the Aqua spacecraft, most detectors on band 6 no longer function, so the algorithm uses SWIR band 7 (2.105–2.155 μm) instead. In areas where forest canopy does not obscure the surface, a pixel is identified as snow when the NDSI ≥ 0.4. Originally proposed for snow mapping from Landsat [5, 6] have stewarded the binary algorithm's current implementation in the NASA EOS data chain. The NDSI ≥ 0.4 threshold generally maps a pixel as snow-covered when its fractional snow cover exceeds 50% [7].

To map snow in forests, the MOD10A1 and MYD10A1 binary products exploit the Normalized Difference Vegetation Index (NDVI) in addition to the NDSI. The NDVI normalizes between near-infrared reflectance, where vegetation is bright, with visible reflectance, where vegetation is dark:

$$NDSI = \frac{R_{NIR} - R_{VIS}}{R_{NIR} - R_{VIS}} \quad (2)$$

To account for the influence of vegetation on the NDSI signal, Klein [8] combined a snow reflectance model with a canopy reflectance model to identify snow-covered forested areas when NDSI < 0.4 but NDVI > 0.1. MODIS bands 1 (0.620–0.670 μm) and 2 (0.841–0.876 μm) are used to calculate NDVI [7]. The approach improves the ability of the binary algorithm to detect snow in moderate canopy where there is some signal in the NDSI. However as the case with any optical satellite, dense canopy can obstruct the signal. The MODIS snow product also uses a surface temperature threshold, based on MODIS product MOD11A1 to eliminate spurious snow cover in areas where the retrieved surface temperature exceeds 280 K [7, 21].

4. Snow Cover Area - Results and Discussion

MODIS Binary snow product for 2000 to 2012 for Alaknanda basin were downloaded and processed. Trend analysis of Snow Cover (2000-2012) shows a slight declining trend (Fig.2).

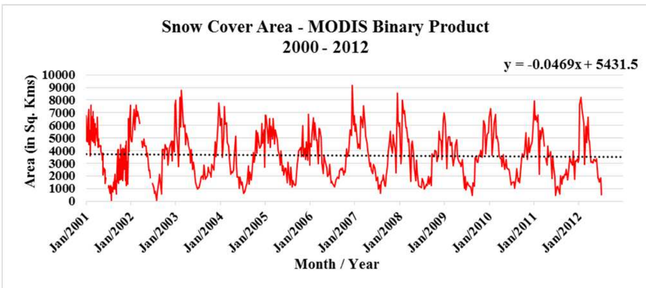


Figure 2: Snow Covered Area derived from Modis-Binary Product for Alaknanda Region for 2000-2012 period.

SCA statistics based on characteristics of the terrain (altitude and aspect) were also analyzed for the years 2000 to 2012 using average annual values. Linear regression analysis resulted in a positive trend in annual variation, but the results were not statistically significant. The maximum SCA was in 2003 and the minimum in 2000 (Fig. 3a). Elevation plays a decisive role in snow accumulation, the statistics of the distribution of snow based on altitude were calculated using SRTM DEM, which was re-sampled from a spatial resolution of 90 to 500 m. Annual variations of snow cover were analyzed for 8 different elevation zones of 1000 m each (Fig. 3b). Linear regression analysis of annual mean SCA showed a positive trend at all elevations though the trend below 2000 m increase in SCA noticed, whereas between 3,000 and 4,000 m its almost stable. The trends however were not statistically very significant.

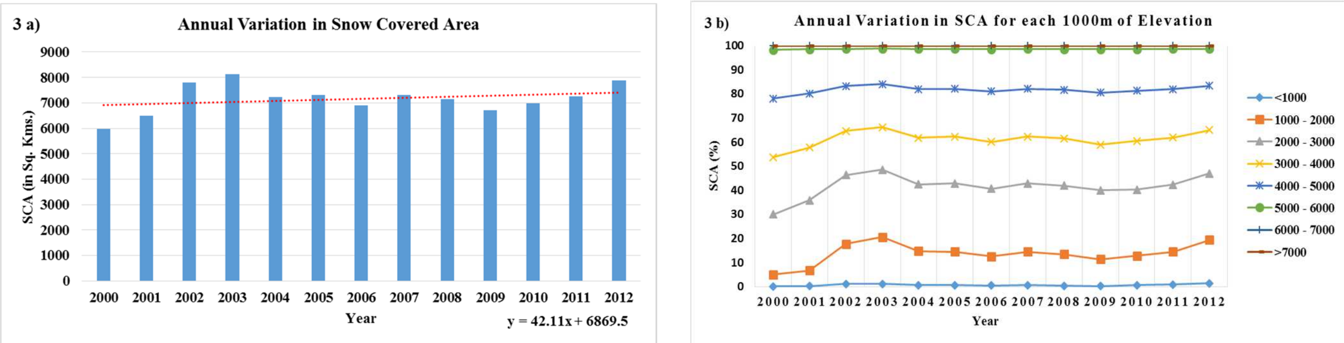


Figure 3: a) Annual variations in Snow cover area, b) Annual variations in Snow cover area for each 1000m of elevation.

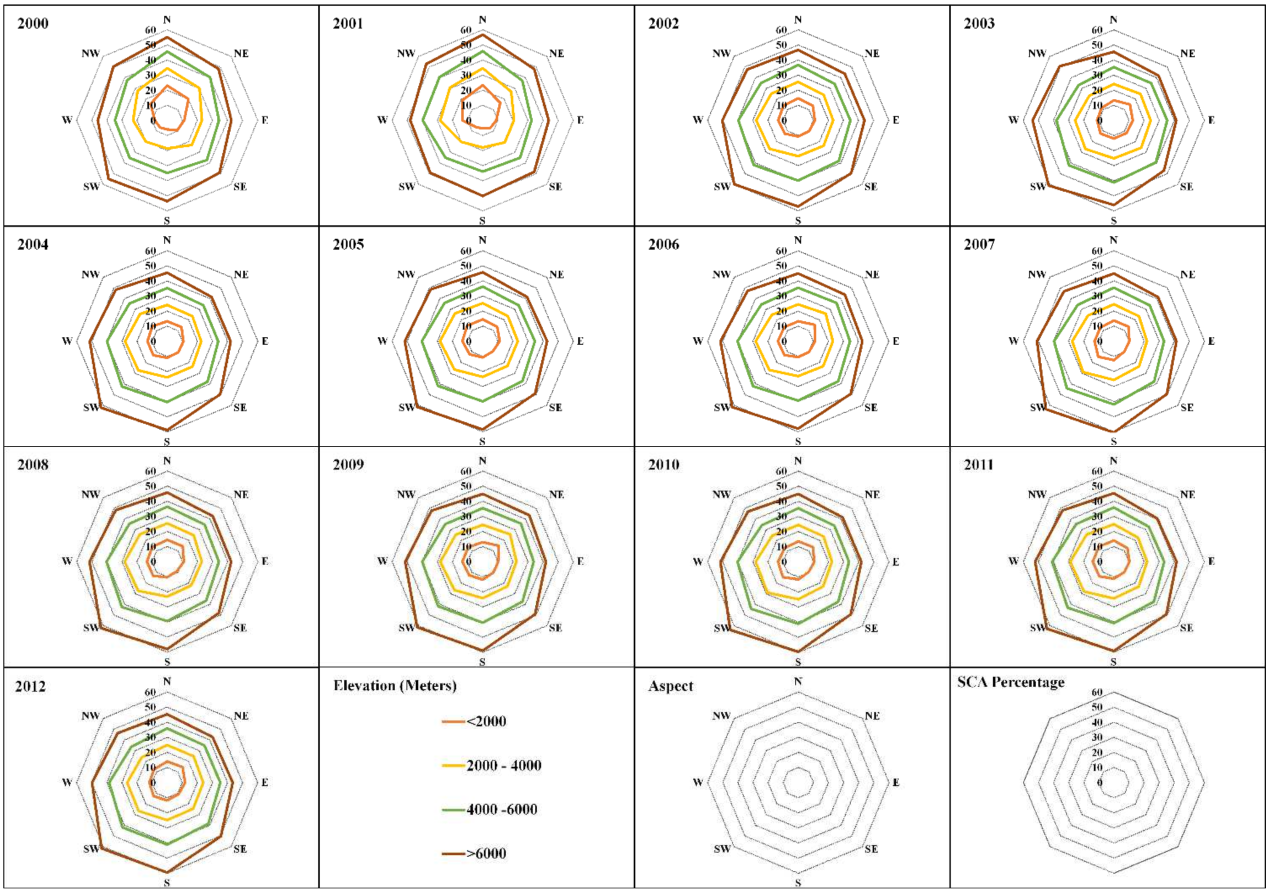


Figure 4: Annual variations in SCA based on elevation and aspect classes. The radius in the polar coordinate shows the SCA (%) and the text indicates aspect classes. The four curves are the mean SCA for the elevation ranges below 2,000 m, at 2,000–4,000 and 4,000–6,000 m, and above 6,000 m.

SCA was also calculated with the help of terrain aspect (8 classes-North, Northeast, East, Southeast, South, Southwest, West and Northwest) for every 2000m elevation. The trends in SCA for altitude classes with respect to terrain aspect shows that maximum snow covered area was in South West slope, while the North East and North West side reported the minimum snow cover area (Fig. 4). Snow cover area was also observed for elevations < 2000m, between 2,000 and 4,000 m, between 4000 - 6,000 m and >6000m, which also showed that SCA is more prominent on the South, South-West and Northern aspect than on East-West aspect. As most of the air moisture is conveyed from the tropical region in the south, which leads to intensive snowfall caused by terrain and/or orographic lifting on the southward slope along the southern edge of the Himalayan region. According to Pu and Xu [22], the northward slope receives less snowfall during autumn and winter. Although the southward slope receives more solar radiation, the snow-albedo effect can maintain a relatively large snow cover on that aspect.

5. Snowline Mapping

The Himalaya is one of the youngest mountain ranges in the world and accounts for nearly 70% of non-polar glaciers. Its direct influence on the climate, hydrology and environment of the Indian subcontinent is well known. As fieldwork in the Himalaya is generally hindered by harsh environmental conditions and logistical difficulties, remote-sensing techniques provide the most suitable means of monitoring changes at higher altitudes for a variety of temporal and spatial scales. Satellite remote-sensing technique has been used extensively for snow-cover monitoring in the Himalayan region with the help of numerous satellite sensors [23]. Snowline altitude and its projection on geographic maps of the area are important indicators of snow coverage. Snowline and snow cover variations from place to place and through time provide much information about regional climate and shorter-timescale meteorological fluctuations.

Generally with the advent of winter the snowline gradually descends along the slope and ablation during summer results in upward movement of the snowline. The seasonal snow cover in the Himalaya is too scattered, due to the rugged relief, to allow a straightforward mapping of the snowline. Here, the application of satellite data in combination with a digital elevation model (DEM) of the Himalayan terrain as a means of assessing snowline elevation has been analyzed. The investigation of snow cover and snowline altitude determination is undertaken for the Alaknanda basin, using data from the LANDSAT satellites for the month of November for the period of 1976, 1990, 1998 & 2010. The images of this specific month is used to so that the maximum upward elevation of snowline after ablation period can be assessed. The Alaknanda basin is highly glacierized and located in the higher-altitude range. In socio-economic terms, this basin is very important, as many hydroelectric power projects are being planned. Due to the high altitude of the basin, stream flow is mostly generated from snow- and glacier-melt runoff which is perennial. Knowledge of the snow cover on a year-to-year basis and changes in snowline altitude are important decision-making parameters when planning hydroelectric power stations.

The snowline is defined as the line delimiting an area with complete snow cover from an area free of snow. The roughness of the surface topography and spatial resolution of the remote-sensing data that determine the extent of snow cover does not allow a direct distinction of snowline and is therefore determined using the SRTM DEM and snow-cover maps extracted from LANDSAT data. A supervised classification method was used to extract snow-cover area from the satellite images. Snow extent was generated for November 1976, 1990, 1998 & 2010. Secondly, with the help of snow cover extent, the borderline of the snow cover derived. From this lower borderline, the lower points of snow cover area were extracted and later joined together to form continuous line to shape averaged snowline. Once line feature representing the snow line have been marked for each time period, the averaged elevation of each snowline was determined on the basis of a digital elevation model.

6. Snowline Mapping – Results and Discussions

Spatial patterns of snowlines are complicated and subject to change, due to the intricate interactions between climate and landforms. There is still a scarcity of automatic methods for digital extraction of a snowline at present. Fig. 5 represents the snowline from Nov.1976-2010. Table 1 and Fig. 6 shows the snowline mean elevation and snow cover extracted from the Landsat image using above methodology and it can be concluded that the snowline has been shifted downward over the period of 1976 to 1998. The maximum snow cover has been notice in the 1998 and during same period the snowline is at lowest elevation of 4287m. Since then the snow cover has decreased in 2010 and snowline raised up to 4659m, though it's still lower than the snowline observed in 1976, which was at 5063m altitude.

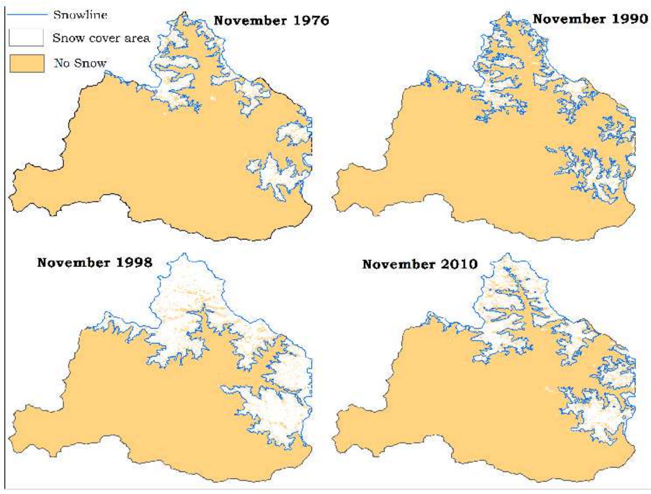


Figure 5: Snow line estimation for November 1976, 1990, 1998 & 2010.

Table 1: Snow cover area & Mean Snow line elevation for November 1976, 1990, 1998 & 2010.

Data	*Snow Cover Area*	*Snowline Mean Elevation*
Nov. 1976	1086.56	5063.66 M
Nov. 1990	1108.80	4945.57 M
Nov. 1998	2620.65	4287.88 M
Nov. 2010	1855.80	4659.00 M

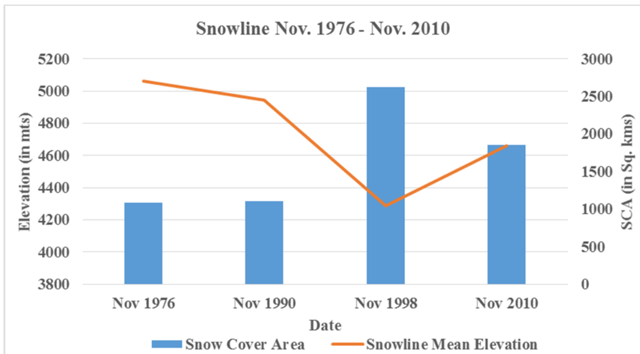


Figure 6: Snow cover area & Mean Snow line elevation for Nov. 1976, 1990, 1998 & 2010.

There are still inadequacies in the actual extraction of snowline due to great spatial complexity, absence of proper and accurate weather data, linking of discrete lower snow points and coarse resolution of data. However, using more number of satellite datasets of different periods for years, taking maximum number of ground observation of weather data, information collected from native people and self-ground truthing are some further milestone in the fine tuning of accurate extraction of snowline.

7. Conclusion

Snow cover area statistics of Alaknanda basin derived from MODIS – Binary snow product from 2000-2012, showed a slight declining trend, though area under snow cover every year during this period is increasing. SCA statistics based on characteristics of the terrain (altitude and aspect) for the years 2000 to 2012 using average annual values of SCA derived from MODIS-Binary product at every 1000m altitude showed a positive trends, though below 2000 m altitude the rate of increase in SCA is faster than between 3,000-4,000 m altitude because maximum condensation happens here below freezing point due to orographic and windward effect. The SCA beyond 4000m altitude is almost stable. However, maximum snow covered area at every elevation zone was found in Southwest slope, while the East and West sides have the minimum snow cover area. While determining the extent of snow cover in the Alaknanda basin, the roughness of the surface topography and spatial resolution of remote sensing data does not allow direct determination of snowline, thus its mapping was accomplished using digital extraction method. It was found out that the snowline altitude decreasedduring 1976-1998 and was at lowest elevation of 4287m. Since then the snowline raised again by 372m in 2010, though it's still 404m lower than the snowline observed in 1976.

The need of regular monitoring of snow covered area and snowline altitude have already been well-outlined. In view of the vastness and rough terrain conditions in the Himalaya, the above approach of extracting snow cover area from MODIS and monitoring its snowline variations can be valuable information for many operational activities, various climatic and hydrological functions predominant in the region and of immense importance for the policy makers and sustainable development of the Alaknanda region. Beside this snowfall and storage of snow in this region prove to be lifeline for the people living in valleys and downstream in areas of Gangetic plains for agriculture, hydropower generation, water management, climate study, avalanche forecasting, flood forecasting, tourism and many other developmental activities that contribute to national economy.

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