Spatio-temporal variability of snow cover in Alaknanda, Bhagirathi and Yamuna sub-basins, Uttarakhand Himalaya

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Advance wide field sensor (AWiFS) data of RESOURCESAT-1 and 2 satellites of IRS series were used to produce snow cover products at 10-day interval from 2004 to 2012 covering October to June of consecutive years for Alaknanda, Bhagirathi and Yamuna sub-basins of Ganga basin in the Himalayan region. The snow products were generated using Normalized Difference Snow Index (NDSI) at a spatial resolution of 56 m using green (B2) and SWIR (B5) channels of AWiFS sensor. Minimum and maximum snow cover was found to be 998, 669, 141 sq. km, and 7874, 5876, 3068 sq. km for Alaknanda, Bhagirathi and Yamuna sub-basins respectively. The areal extent of snow was higher than the mean during the years 2004–2005, 2007–2008 and 2011–2012 for all sub-basins. Mean of monthly fluctuations between maximum and minimum snow cover were recorded as 3105, 2305, 1235 sq. km corresponding to variation in snow line altitude of 1613, 1770, 1440 m respectively. A subtle increase in the snow cover has been observed in these three sub-basins during 2004–2012. The results matched well with the variations in temperature taken from nearby ground weather stations. Snow cover products were analysed to understand spatio-temporal variability of accumulation and ablation of snow in the three sub-basins. Monthly fluctuations in snow cover were high during accumulation period than in ablation. This work also attributes in generation of long-term database which will be useful for understanding climatic variations over Himalayan region.

Keywords: Ablation, AWiFS, Ganga, NDSI, snow cover.

EXTENT of the snow cover is considered as an important parameter for numerous climatological and hydrological applications. It keeps Earth's radiation budget in balance as it reflects a large portion of the insolation[1–4]. Several fundamental physical properties of snow modulate energy exchanges between the snow surface and the atmosphere[5]. The surface reflection of incoming solar radiation is important for the surface energy balance[6]. The higher albedo for snow causes rapid shifts in surface reflectivity in autumn and spring in high latitudes. The high reflectivity of snow generates positive feedback to surface air temperature. Groisman *et al.*[7,8] observed that snow cover exhibited the greatest influence on the Earth radiation balance in spring (April to May) when incoming solar radiation was greatest over snow cover areas. In terms of the spatial extent, snow cover is second largest component of the cryosphere and covers approximately 40–50% of the Earth's land surface during Northern Hemisphere winter[9–11]. The second role which snow precipitation plays is in feeding the glaciers of the world. Annual precipitation of snow feeds the accumulation zone of the glaciers and is considered as an important parameter for glacier mass balance studies. The third major importance of snow lies in its melt runoff. Snowmelt is the source of freshwater required for drinking, domestic, agricultural and industrial sectors especially in middle and high latitudes[3,12]. Himalayas being the loftiest mountains of the world are abode of snow and glaciers. The mountains are drained by three major rivers, i.e. Indus, Ganga and Brahmaputra and their tributaries. The higher altitudes of these three major rivers situated in temperate climate receive heavy snowfall during winters. The snowfall feeds glaciers of Himalayas and almost 30–50% of annual flow of all the rivers originating from higher Himalayas comes from its melt run-off[13,14]. Increase in atmospheric temperature can influence snowmelt and stream runoff pattern which is considered as crucial for determining hydropower potential[15,16]. However, mapping and monitoring of seasonal snow cover using conventional methods is a challenging task especially in harsh climatic conditions and rugged terrain of Himalayas. Remote sensing has emerged as a useful technique for snow cover mapping and monitoring. Snow cover monitoring using satellite images started from TIROS-1 in April 1960 (ref. 17). Since then, the potential for operational satellite-based mapping has been enhanced by the development of sensors with higher temporal frequency and higher spatial resolution. Sensors with better radiometric resolutions, such as MODIS and AWiFS, have been used for generating the snow products[9,18,19] and improvements over vegetation[20,21]. Snow cover extracted from earlier data and snow products prepared using recent satellite images by auto-extraction approaches have been analysed to know the trends in the snow cover variability in many other studies. For example, Singh *et al.*[19], have shown through the analysis of MODIS data that there is an increasing trend of snow cover in Indus Basin, whereas Ganga and Brahmaputra basins have shown subtle decreasing trend during the same period. A decrease in snow-covered areas has been observed globally since the 1960s (refs 11, 22). In some region such as China, a trend of increasing snow cover has been observed from 1978 to 2006 (ref. 23) based on utilization of SMMR/SMMI data.

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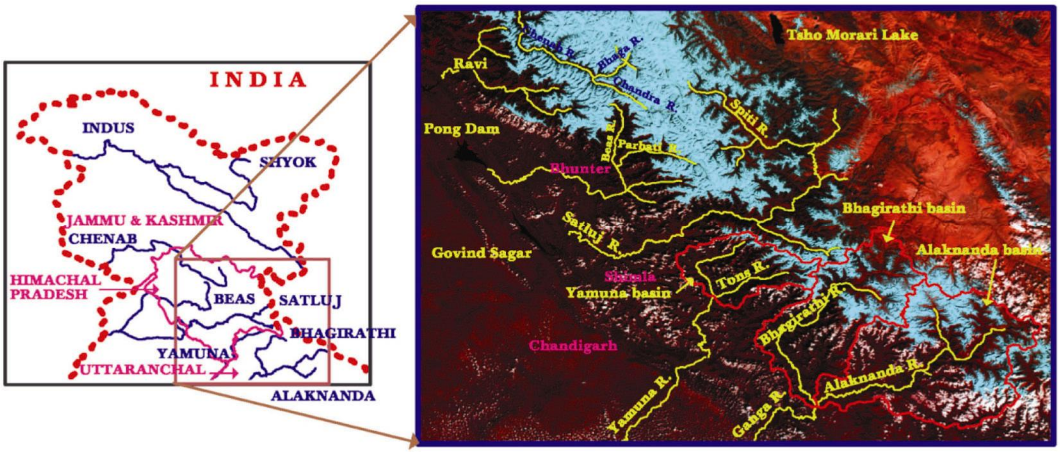

Figure 1. Location map of Alaknanda, Bhagirathi and Yamuna sub-basins.

This study discusses the spatio-temporal variability of areal extent of snow to understand the accumulation and ablation patterns at fine spatial resolution for consecutive eight years between 2004 and 2012 for three major sub-basins Alaknanda, Bhagirathi and Yamuna of Ganga Basin in Uttarakhand, India. Areal extent of these three sub-basins is 11,090, 7,438, 3,527 sq. km respectively (Figure 1). AWiFS data of RESOURCESAT-1 and 2 satellites were used to generate snow cover products.

This study has been carried out using data from AWiFS sensor of RESOURCESAT-1 and 2 satellites having spatial resolution of 56 m. Detail specifications of AWiFS sensor are given in ref. 24. Approximately 640 AWiFS scenes for a period of 8 years for October to June from 2004–2005 to 2011–2012 were used. A master image of AWiFS data of the study area was prepared using reference points from orthorectified Landsat TM data. All the AWiFS scenes from October to June for 2004–2012 were geocoded using master image. Normalized difference snow index (NDSI) approach was developed using AWiFS data for extracting snow cover from satellite sensors with green and SWIR bands (eq. (1))

$$\mathrm{NDSI} = \frac{\mathrm{Reflectance}_{\mathrm{Green}} - \mathrm{Reflectance}_{\mathrm{SWIR}}}{\mathrm{Reflectance}_{\mathrm{Green}} + \mathrm{Reflectance}_{\mathrm{SWIR}}}. \quad (1)$$

To estimate NDSI, DN numbers are converted into TOA (top of atmosphere) reflectance. This involves conversion of digital numbers into the radiance values, known as sensor calibration, and then reflectance from these radiance values was estimated. Various parameters needed for estimating spectral reflectance are maximum and minimum band pass spectral radiances and mean solar exo-atmospheric spectral irradiances in the satellite sensor bands, satellite data acquisition time, solar declination, solar zenith and solar azimuth angles, mean Earth–Sun distance, etc.[25,26]. Snow extent was estimated at an interval of 5 and 10 days, depending upon the availability of AWiFS data. Individual scenes were analysed to generate the 5 days snow cover product. In 10-days product, three consecutive scenes have been analysed, if available[18,27]. To differentiate water and snow, water bodies were marked in pre-winter season and then masked in the final products during winter. Topography influences the areal extent of snow cover of the rugged terrain. Topographic correction has been applied to assess the error for AWiFS images of 2008–2009 using ASTER DEM with the help of the orthorectified module of the ERDAS Imagine image processing software. Comparative analysis was carried out for snow cover areal extent on orthorectified product before and after topographic correction.

Subset of snow cover products was made as per sub-basin boundary of Alaknanda, Bhagirathi and Yamuna and areal extent of snow was estimated. Figure 2 shows an example of snow cover products of Alaknanda sub-basin corresponding to December and February. Mann–Kendall test was performed to evaluate the statistical significance of the trend. Altitude zones of sub-basins were made by overlaying the contours derived from SRTM DEM. The DEM product has 90 m spatial resolution and vertical root mean square error of 16 m (ref. 28). DEM is converted into contour map at 1000 m interval using ARC GIS. Hypsographic curves were prepared to estimate area–altitude distribution indicating the area covered in some definite altitude zones for each sub-basin. The curves were also used to estimate altitude of snow line based on the snow cover extent. The 10 daily products were converted to polygon layer using raster to vector conversion. Intersection analysis of GIS is used between snow product and altitude zone to get snow cover area in each altitude zone. Snow cover area under each altitude zone was estimated using GIS for their comparative analysis to understand the effect of altitude on accumulation and an ablation pattern at sub-basin scale, and varies from 500 to 7000 m for all the sub-basins. TM data were used to geo-reference AWiFS images. Air temperature

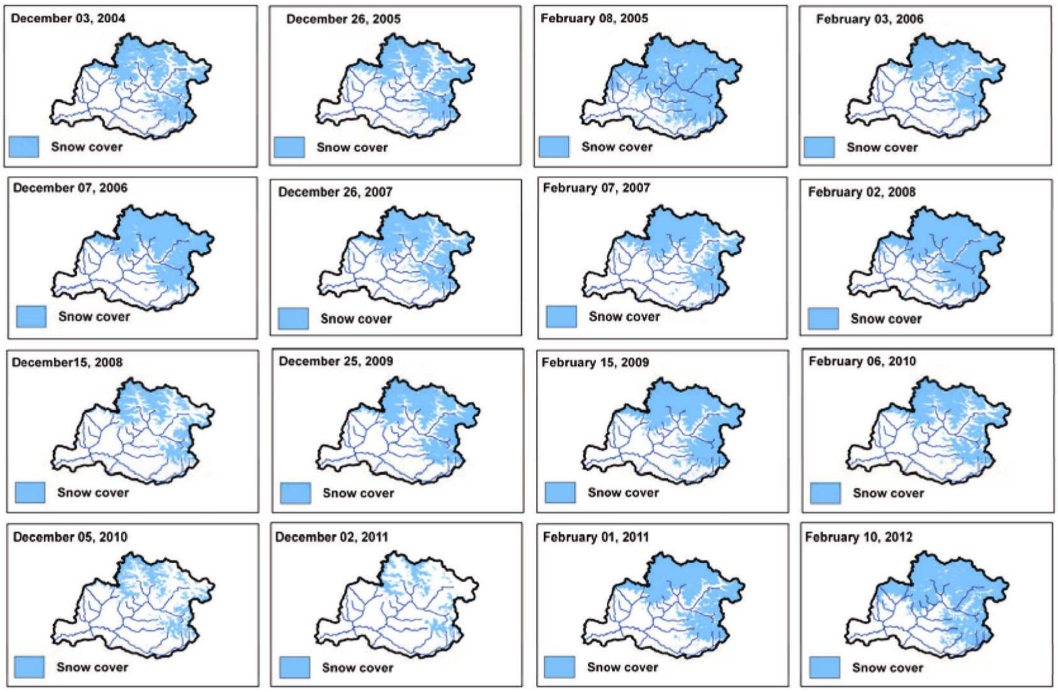

Figure 2. Snow cover map for December and February in Alaknanda sub-basin.

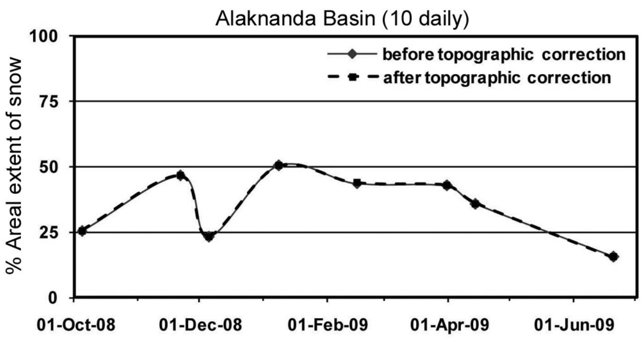

Figure 3. Accumulation and ablation pattern on orthorectified product of AWiFS before and after topographic correction.

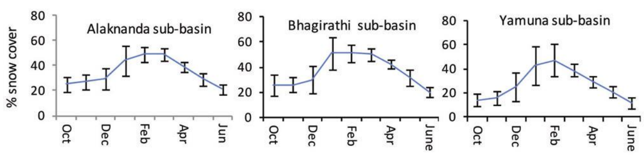

Figure 4. Monthly average snow cover for the period 2004–2012 along with $\pm 1\sigma$.

(maximum and minimum) data of eight years at Dehradun, located near these three sub-basins were analysed and compared with snow areal extents.

Considering the monthly averages, the results show that snow cover reached its maximum in January 2012 for all three sub-basins, corresponding to 71%, 79% and 87% (7874, 5876 and 3068 sq. km) of the total area for Alaknanda, Bhagirathi and Yamuna sub-basins respectively. The minimum was observed during October 2012 which corresponds to 9%, 9% and 4% (998, 669 and 141 sq. km) of the total area respectively. Analysis of orthorectification has shown a negligible difference of 7 sq. km in the entire basin area. A comparison of accumulation and ablation pattern with orthorectified product has shown almost no change (<1%) for 2008–2009 before and after topographic correction (Figure 3).

Monthly average snow cover for 2004–2012 has been shown with $\pm 1\sigma$ (Figure 4). Most of variations were observed during accumulation period, especially in Yamuna sub-basin which is located at lower altitude ranging from 1000 to 6100 m. Alaknanda sub-basin has shown relatively low variation in standard deviation for monthly averaged snow cover for 2004–2012 in comparison to other two sub-basins. However, Bhagirathi shows higher snow cover area which could be due to more area under high altitude region as shown in the hypsographic curve of all sub-basins (Figure 5).

If total snow cover over a year is considered, then it is seen that areal extent of snow for 2004–2005, 2007–2008 and 2011–2012 was higher than the mean of total snow cover over eight years. Snow cover area has shown slight increasing trend for all sub-basins from 2004 to 2012 (Figure 6), however, it was not found to be statistically significant. Minimum snow cover has not shown any variation which corresponds to negligible change in maximum snow line altitude, whereas maximum snow cover has shown an increasing pattern which corresponds to lowering of snow line altitude during the observed period that means snow fall reaches lower region.

However, a decreasing trend in snowfall has been reported over all the Himalayan mountain ranges from 1988 to 2006 using ground observations[29].

The pattern of accumulation and ablation also differs from one basin to other. Annual accumulation and ablation pattern of snow cover of each sub-basins from 2004 to 2012 is shown in Figure 7. Frequent fluctuations of snow cover are observed during accumulation period. These fluctuations are being attributed to frequent snowfalls and continuous melting in the lower altitude regions. However, this phenomenon is not true for ablation period. As the snow line progressively moves up during ablation months (April to June), fluctuations in snow cover on higher altitudes are not observed. Yamuna sub-basin has shown accumulation and ablation throughout the year in comparison to other two sub-basins as 77% of the area falls below 4000 m altitude. Not much change was observed in the gradient of ablation curves for all the years which indicates comparable time and rates of melting.

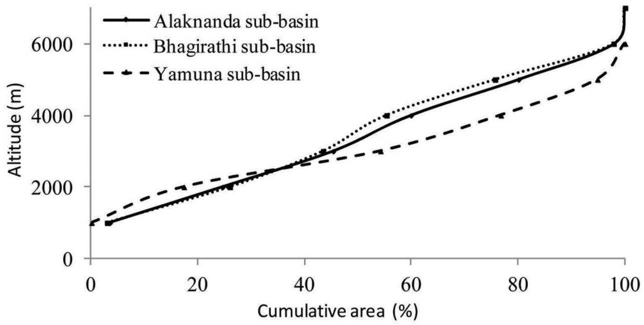

Figure 5. Hypsographic curve giving percentage cumulative area for all three sub-basins.

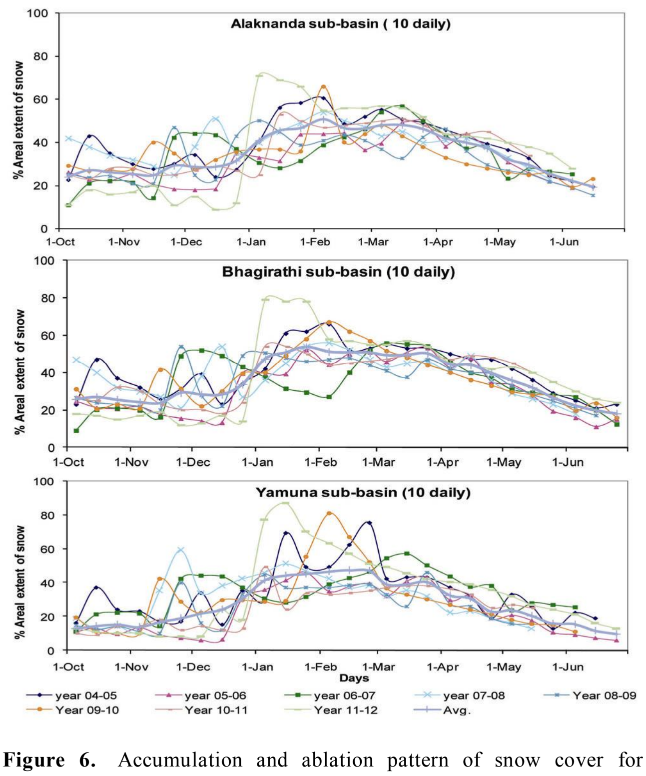

Figure 6. Accumulation and ablation pattern of snow cover for Alaknanda, Bhagirathi and Yamuna between 2004 and 2012.

Area–altitude distribution indicating the area covered in some definite altitude zones was estimated for each sub-basin and the distribution is shown by hypsographic curves. Hypsographic curves of Yamuna sub-basin show gentle slope among all the three sub-basins which indicates Yamuna sub-basin to be located in lower altitude zones than Bhagirathi or Alaknanda sub-basins. However, it was observed that 60% of the area of Bhagirathi sub-basins falls in higher altitudes in comparison to Alaknanda sub-basin. Mean monthly minimum and maximum snow cover was computed as 2329, 1488, 423 and 5434, 3793, 1658 sq. km for Alaknanda, Bhagirathi and Yamuna sub-basins respectively. Minimum and maximum snow line altitudes were determined as 3311, 3482, 2922 and 4924, 5232, 4362 m respectively (Table 1). This shows a variation of 3105, 2305 and 1235 sq. km in snow cover corresponding to 1613, 1770 and 1440 m. fluctuation in snow line altitude. It has been observed that maximum variation takes place in 3000–4000 m altitude zone in all the three sub-basins corresponding to 0–95%, 0–100% and 0–95% change in snow cover respectively (Figure 8). It is probably due to high atmospheric temperature and heat conduction from ground in this altitude range. In 4000–5000 m zone, the snow cover varied from 4% to 100%, 11% to 100% and 9% to 100% for three sub-basins as this zone is characterized by occurrence of glacier ice, inducing low geothermal heat and moderately low air temperature. Snow cover does not vary much above 5000 m amsl and this zone remains mostly above permanent snow line throughout the year.

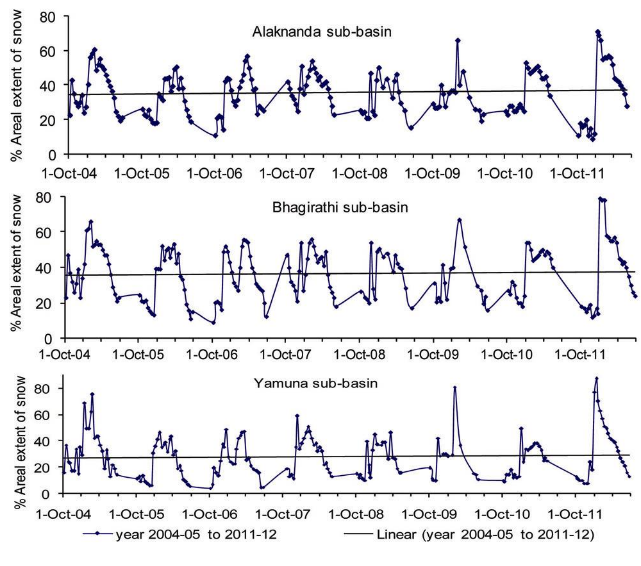

Figure 7. Variation in snow cover areal extent and its trend from 2004 to 2012.

Table 1. Mean monthly areal extent of snow and snow-line altitude from 2004 to 2012

Sub-basin	Alaknanda		Bhagirathi		Yamuna	
Month	Area (sq. km)	Altitude (m)	Area (sq. km)	Altitude (m)	Area (sq. km)	Altitude (m)
October	2773	4812	1934	4946	494	4262
November	2994	4740	1934	4946	564	4189
December	3216	4654	2231	4738	882	3958
January	4880	3683	3793	3482	1517	3174
February	5434	3311	3793	3482	1658	2922
March	5434	3311	3719	3548	1376	3408
April	4325	4053	3198	3995	1023	3846
May	3216	4654	2380	4634	741	4052
June	2329	4924	1488	5232	423	4362

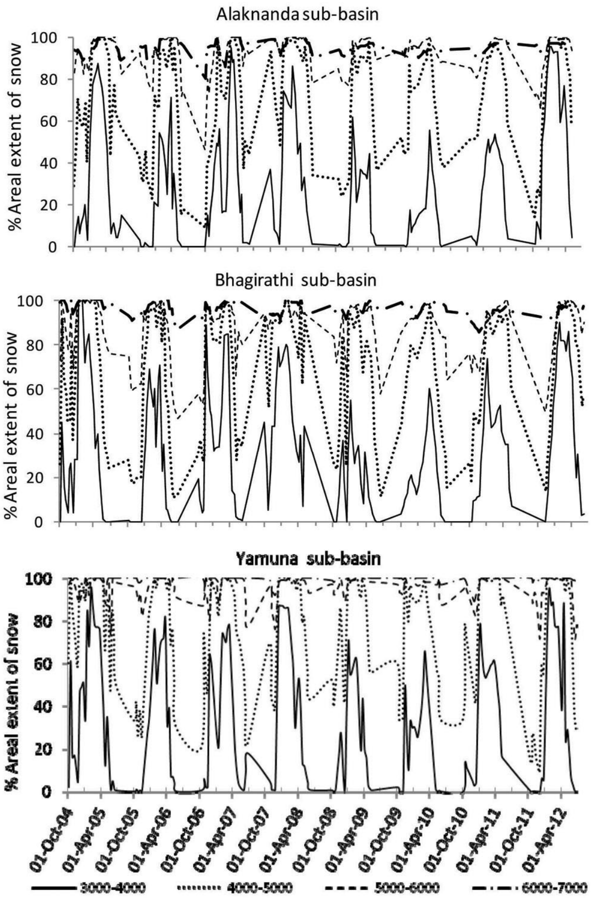

Figure 8. Snow cover variation for various altitude zones at 1000 m interval.

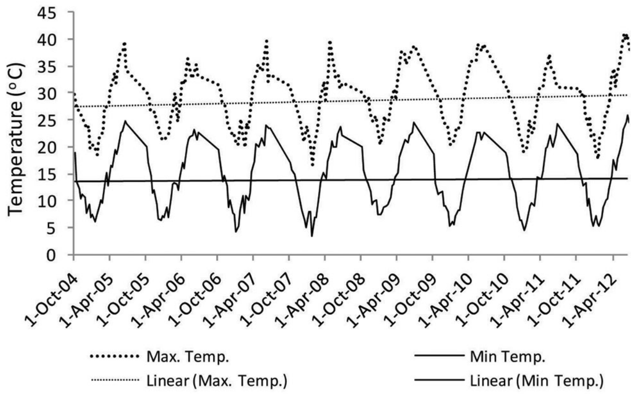

Figure 9. Minimum and maximum air temperature (10 day average) at Dehradun from 2004 to 2012.

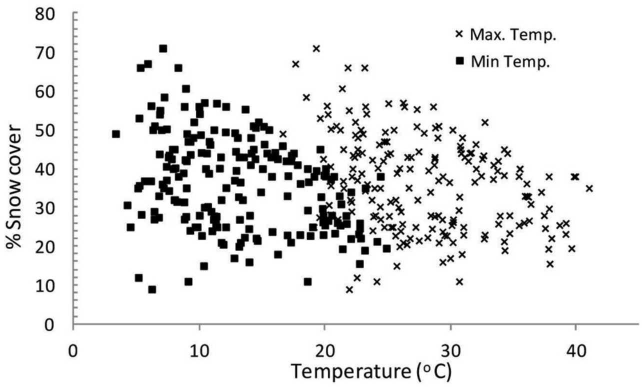

Figure 10. Scatter plot showing snow cover with air temperature for Alaknanda sub-basin.

Air temperature data of Dehradun (www.TuTiempo.net) from 2004 to 2012 is depicted in Figure 9, which shows subtle increasing trend for both minimum and maximum 10 daily average temperatures. Rise in temperature and reduced snow cover were observed in May and June 2012 which also gets reflected in high snow line for 2012. Percentage change in areal extent of snow in Alaknanda sub-basin had inverse correlation with temperature data (Figure 10). It shows a right angle pattern because of maximum variation during accumulation and minimum during ablation period.

The following conclusions have been drawn from this study.

- A subtle increase of approximately 2% in snow cover has been observed in Alaknanda and Bhagirathi sub-basins and 1% for Yamuna sub-basin. However, the increase in snow cover observed was found to be statistically insignificant.
- Maximum fluctuation in monthly average snow cover has been observed in Yamuna subbasin as it is located at lower altitude in comparison to other two sub-basins.

- Variations in maximum and minimum snow cover area for Alaknanda, Bhagirathi and Yamuna sub-basins have been observed as 3105, 2305 and 1235 sq. km, whereas the respective change in altitude of snow line was observed as 1613, 1770 and 1440 m. This could be probably explained by area–altitude distribution estimated using hypsographic curve of all the sub-basins.
- Variation in snow cover changes has been observed higher in accumulation period than in ablation period for all the sub-basins. Snow line reaches its lower altitude during the accumulation period where fluctuations in temperature are frequent.
- A large variation in snow cover was observed in lower altitude zones like 3000–4000 m and 4000–5000 m, than in region above 5000 m where the accumulation zone of glaciers exists.
- Mean monthly snow line altitude was observed relatively high for Alaknanda and Bhagirathi in comparison to Yamuna sub-basins.

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