Monitoring snow cover in the Himalayan–Karakoram basins using AWiFS data: significant outcomes

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Snow cover, the second largest component of the Earth's cryosphere, controls the hydrology of basins, mass balance of glaciers and climate at the local, regional and global scale. Therefore, it is regularly observed through the Earth Observation (EO) dataset at fine, medium and coarse resolution to understand the impact of its variability in land–atmospheric interactions. The present study analyses of the variability of snow cover area within the Himalayan–Karakoram (H–K) region based on snow products generated by the NDSI approach using data from AWiFS sensor of Resourcesat satellites at an interval of five and ten days. The study covers 33 sub-basins of the Indus, Ganga and Brahmaputra basins in the H–K region. For analysis and presentation, results of the Indus basin have been further divided as Indus–North, Indus–South, Chenab and Satluj basins due to the large basin area. A high spatial and temporal variability in the seasonal snow area was observed in the entire H–K region based on the sub-basin-wise 35,910 snow cover products generated between 2004 and 2019. A higher percentage of snow area in the Karakoram region than in the other sub-basins was observed throughout the years. Though interannual trends of snow cover area remained more or less stable in all the basins, a decreasing trend was observed in October in a few basins and an increase in snow area in the Indus–North region during December and January.

Keywords: Climate change, cryosphere, intrannual trends, river basins, satellite data, snow area variability.

SNOW precipitation covers about 40–50% of the surface land during winter in the Northern Hemisphere and thus becomes second largest component of the cryosphere[1,2]. A recent study using CloudSAT data estimated a volume of 1773 km^3 of snow over mountains regions, which contributed to almost 5% of the global snow accumulation[3]. Snow accumulation governs the annual mass balance of glaciers and ice sheets, and the production of fresh meltwater feeding the rivers. Due to its high albedo, one of the most important impacts of varying snow mass has been to understand atmospheric circulation[4–9]. Snow cover is one of the most sensitive natural covers on the Earth's surface, which can change its phase with a subtle change in the atmospheric temperature. The current global warming trend with a rise of 0.85°C temperature between 1880 and 2012, as reported by the Intergovernmental Panel on Climate Change (IPCC)[10], can alter snow precipitation patterns on the Earth, thus affecting several industrial and domestic sectors, including agriculture, hydropower and tourism[11–16]. Understanding its role in the environment as a vital organ of the Earth's hydrological, weather and climatological system, snow has been monitored for more than 3–4 decades at the regional and global scale using orbiting satellites[17].

There are six primary variables of snow retrieved using satellite data, namely snow cover area (SCA), snow area duration (SCD), snow albedo (SAL), snow water equivalent (SWE), snow grain (SG) and dry/wet snow (WS), which have been used to study the hydrology and climatology of a region[18–21]. Among these, SCA is a directly observable parameter and has more certainty than the other derived parameters. MODIS snow products have been widely used to understand spatio-temporal variability of SCA[22]. SWE has been estimated globally using passive microwave data at a very coarse resolution with high uncertainties in the high relief Himalayan–Karakoram (H–K) region[23,24]. Many studies have been carried out regionally/globally for assessing SCA in the Northern Hemisphere, including the H–K region[25,26], but only a few are available at a fine spatial and temporal resolution over the H–K region. SCA assessment and monitoring are important for the H–K region as its snowmelt contributes approximately 30–50% of the annual flow of all the perennial Himalayan river[27,28]. It flows through the drainage system of the Indus, Ganga and Brahmaputra rivers and thereby supports a large population in the mountains and plains of these rivers before they enter into the Arabian Sea and Bay of Bengal. A study suggests that annual snowfall may reduce by 30–70% over the Indus, Ganga and Brahmaputra basins by 2071–2100 under a climate model projection scenario (RCP8.5)[29].

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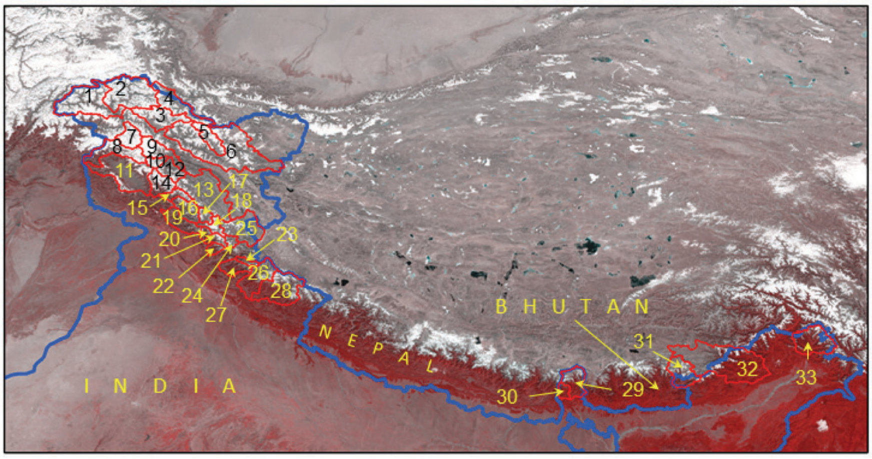

Figure 1. Image showing the Himalayan–Karakoram (H–K) region and 33 sub-basins included in this study for snow cover area data analysis. The sub-basins shown here are the same as those reported in SAC[32].

Due to its role in the Earth's land–atmospheric–hydrologic processes and its impact on the society and environment, monitoring of snow area in major parts of the H–K region has been carried out at the Space Applications Centre, Indian Space Research Organisation, Ahmedabad using AWiFS data. Results and analysis of the monitoring have been discussed here, along with reasons for the Karakoram anomaly and mass gain of the glaciers[30,31].

Extent of the study region

The present study area covers various sub-basins (33 in number) of the Indus, Ganga and Brahmaputra basins (Figure 1). The snow and glacier mapping of these sub-basins has already been done earlier[32,33]. Drainages of sub-basins 1–13 flow to the River Indus. Drainages of sub-basins 14–19 flow to the Chenab River which further joins the Indus. Drainages of sub-basins 20–25 flow to River Satluj, which also joins the Indus. Sub-basins 26–28 are part of the Ganga river system. Drainages of sub-basins 29–33 flow to the Brahmaputra River. Chenab and Satluj rivers are sub-basins of the Indus, but since their area is very large, they are also treated as basins. The Indus sub-basins have been grouped into two: sub-basins draining through the Karakoram mountains and sub-basins in the Ladakh region. The Indus sub-basins are mainly a part of Jammu and Kashmir (J&K) and Ladakh, whereas Chenab and Satluj sub-basins are a part of Himachal Pradesh. Sub-basins of the Ganga drain through Uttarakhand, whereas sub-basins of the Brahmaputra drain through Sikkim and Arunachal Pradesh.

Data and methodology

The AWiFS sensor was launched on the Resourcesat series of satellites of ISRO, first on 17 October 2003. It has a spatial resolution of 56 m with four spectral bands, including the SWIR band. Its repetivity on any part of the Earth's surface is five days due to its wide swath. AWiFS data were obtained from the National Remote Sensing Centre (NRSC), Hyderabad, after being subjected to basic geometric and radiometric corrections. The AWiFS images were further georeferenced with the master images using a second-order polynomial resampling method to improve the geometric accuracy of the images.

The availability of green and SWIR bands has made it possible to generate normalized difference snow index (NDSI) on a per-pixel basis. This index helps in the identification of snow pixels on AWiFS images. An algorithm for this procedure has been developed earlier. Ground validations of spectral values were also used in the development of algorithm[34]. A threshold value equal to or more than 0.4 was assigned to extract snow using this algorithm[34]. The NDSI-based technique is also considered to be useful in mountainous regions to successfully map the snow pixel under mountain shadow[1]. Thus, snow area products generated using AWiFS data and NDSI algorithm have been used in understanding the trends of accumulation and ablation of snow over the H–K region since 2004 (refs 35, 36). The present study is an extension of earlier results; here we take data up to 2019 and compartmentalize the trends on a monthly basis. These can be considered one of the best regular snow area products in terms of resolution and repetivity, which provides an opportunity for close monitoring of this climate variable. One set of examples of snow products at sub-basin scale is shown in Figure 2 for the Parbati sub-basin for 2019.

Results and discussion

The Himalayan Arc is spread over a large area, but varying trends in snow areas can be observed across various climate zones distributed across the H–K region (Figure 3). Two aspects of snow area analysis are discussed here: (i) snow

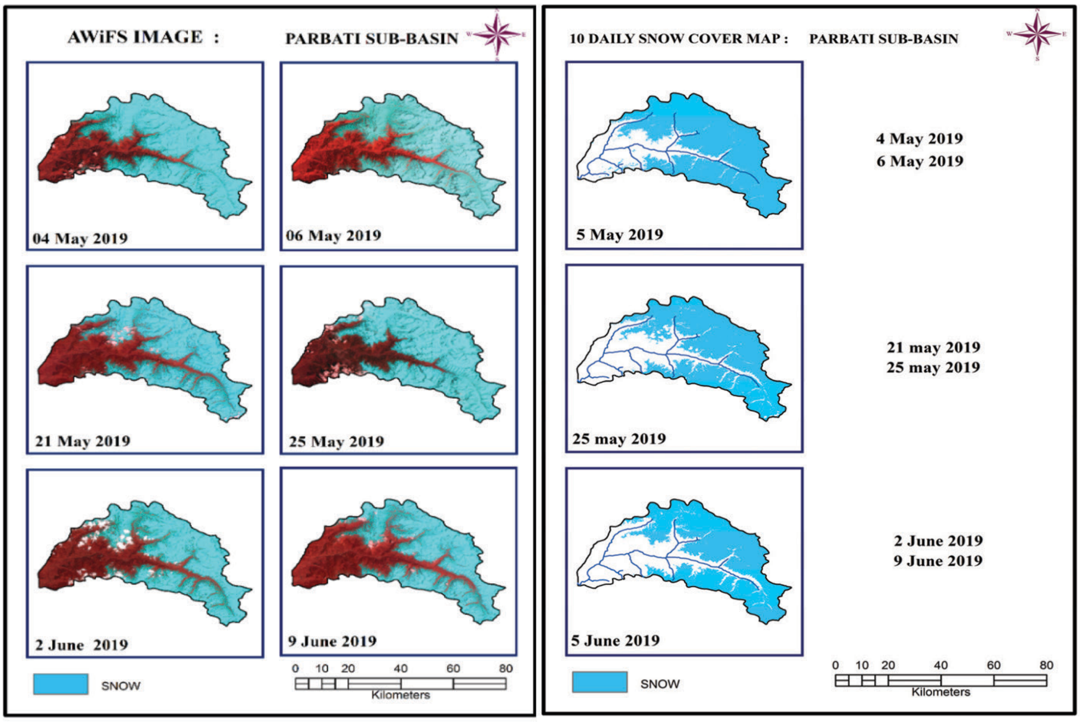

Figure 2. AWiFS images of the Parbati sub-basin and their respective 10 days snow products.

Table 1. Minimum and maximum snow area in various basins under study over the last 15 years

Basin	Sub-basins	Minimum snow area (km^2) and year	Maximum snow area (km^2) and year
Indus–North	Gilgit, Hanza, Shigar, Shasgan, Nubra, Shyok	3697 (October 2016)	64027 (January 2019)
Indus–South	Astor, Kisanganga, Shigo, Drass, Jhelum, Suru, Zanskar	2795 (October 2016)	50262 (January 2012)
Chenab	Warwan, Bhut, Miyar, Bhaga, Chandra, Ravi	1765 (November 2016)	20208 (February 2019)
Satluj	Beas, Parbati, Jiwa, Baspa, Pin, Spiti	1111 (October 2016)	15424 (January 2013)
Ganga	Bhagirathi, Yamuna, Alaknanda,	1846 (November 2016)	16826 (February 2014)
Brahmaputra	Tista, Rangit, Tawang, Subansiri, Dibang	1918 (October 2011)	27119 (October 2008)

phenology or intraannual variability in accumulation and ablation of snow, and (ii) interannual snow area variations across the H–K region. The first aspect is associated with hydrology of sub-basins and mass balance of glaciers. The second aspect is linked with the impact of climate on snow areas in the H–K region compared to global trends. Table 1 shows the maximum and minimum snow area in the sub-basins under study over the last 15 years.

Intraannual variability

The snow area data for 33 sub-basins during the accumulation and ablation period were averaged in six zones for a period of 15 years (Figure 4). The slope of the curves shows the rate of accumulation and ablation with respect to time. Although accumulation differed for each sub-basin, the slope of the ablation curves indicated that the rate of ablation over the years was similar. There was no anomalous increase or decrease in the ablation of snow. One of the most important observations was that the initial storage of snow mass varied from one sub-basin to another. For example, initial storage in the Chenab, Satluj, Indus–South, Ganga and Brahmaputra basins remained below 25% at the beginning of the accumulation season. Whereas the sub-basins located on the northern side across the Indus showed a higher percentage of snow area, which was also observed during the ablation months. Another study also supports this view that among all the river basins, the Indus basin is most dependent on snow and ice melt for its water resources[37] and large parts of the basin are snow-covered for prolonged periods during the year[38]. Higher snow area increases the mass of the glaciers and protects glacier ice from rapid melting. Due to higher density of ice, glacier ice has more water equivalent than snow, which remains protected under snow in the accumulation months. The increased load of snow can reduce the pressure melting point below the glaciers and

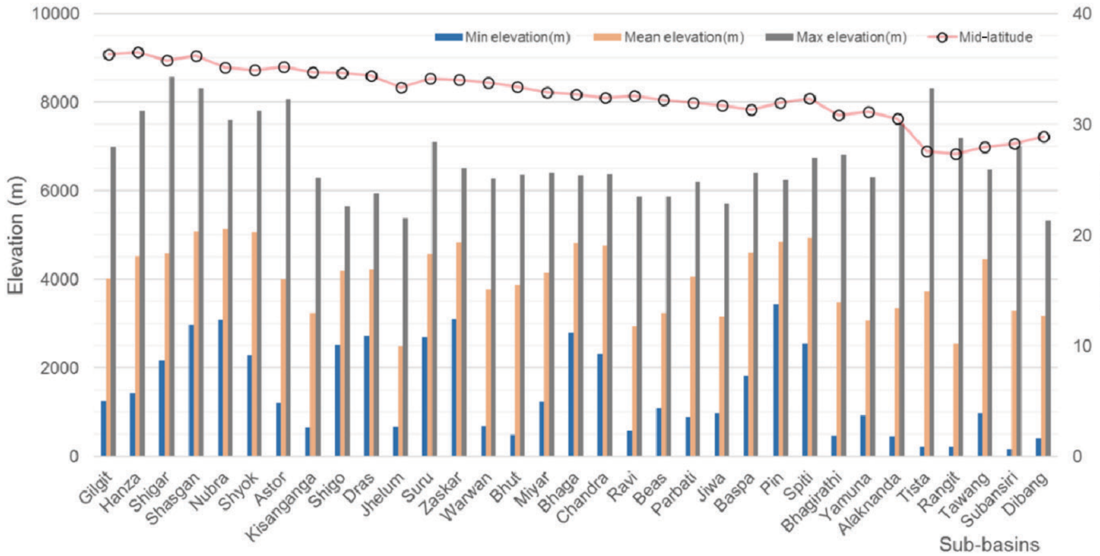

Figure 3. Sub-basin-wise variation of minimum, maximum, mean altitude and latitude manifested in the variation of accumulation and ablation of snow area.

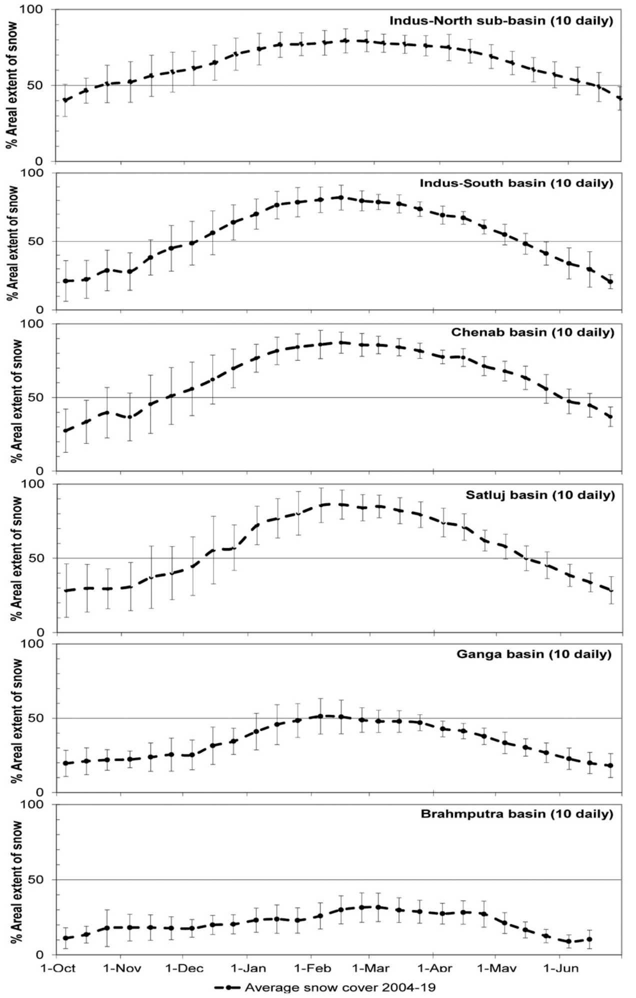

Figure 4. Variability in snow accumulation and ablation pattern of 10 days along with mean and standard deviation between 2004 and 2019.

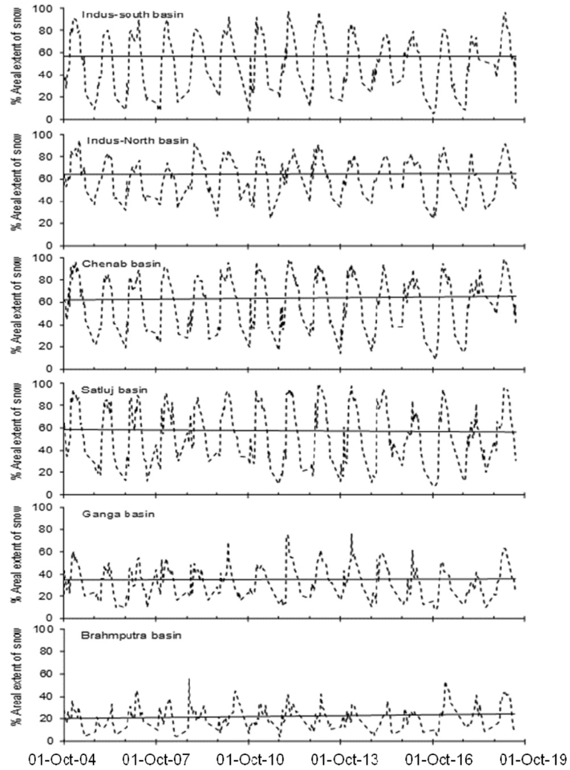

Figure 5. Variation in snow area (percentage change) and its trend between 2004 and 2019 over sub-basins distributed in the Himalayan region.

lead to slippage of ice mass. This is probably the reason for the anomaly in the Karakoram region, where glaciers have shown expansion or surging[30,38]. Snow area plays a major role in mass balance variations of glaciers[39]. These results are in good argument with the findings of area change of glaciers mapped in the H–K region[35].

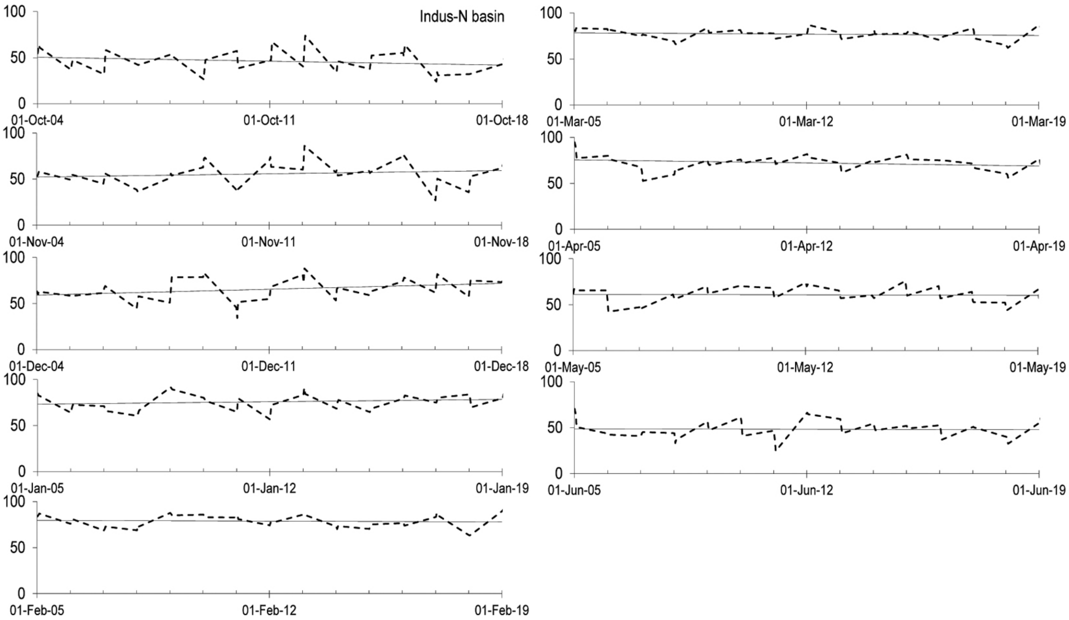

Figure 6. Monthly break-up of trends of snow area between 2004 and 2019 for the Indus–North sub-basins. Data for October show a slightly decreasing trend, while those for December and January show increasing trend.

Another aspect of snow cover is its potential in terms of water equivalent. The maximum snow cover extent went up to 80–90% in the Indus–North, Indus–South, Chenab and Satluj basins, but not in the Ganga and Brahmaputra basins, indicating low freshwater storage potential from snowmelt for the later two basins. The curves of snowmelt during the ablation season also indicate contribution in run-off from snowmelt; if the slope of the curve is steep, melt will be higher. In terms of temporal variability, the standard deviation was higher in the accumulation months than in the ablation months due to erratic snowfall and rainfall scenarios during the monsoon season. This suggests that ablation or melting of snow from April to June has been same over the past 15 years, which applies to all basins. Standard deviation in the accumulation period from October to February varied from one basin to another, suggesting high variability in snowfall. It started early in the Western Himalayas and late in West–Central, Central and Eastern Himalayas. Heterogeneity of the accumulation and ablation pattern along the Himalaya–Karakoram Arc can be attributed to variation in altitude and latitude (Figure 3). A dip in snow area during the accumulation months was clearly distinguishable (winter dip) in the Indus–South and Chenab basins (Figure 4), which is associated with snowfall in October followed by melting in November and December.

The percentage of snow area in each sub-basin is an important input in snowmelt run-off of the sub-basin. Higher the percentage of snow area, more is its contribution to snowmelt run-off. The sub-basins of Indus–North remained covered with snow for most of the year, but in the Brahmaputra basin snow area remained low with no steep rise. This indicates that solid precipitation is low in the Eastern Himalayas. In Northwestern Himalaya, the snow ablation curves have less slope than in the other regions, which reflects that the entire snow mass does not melt away even up to the end of the ablation period. It is also true that sample sub-basins are less in number in the Ganga and Brahmaputra basins than in the Indus basin.

The accumulation was observed to increase sometime after February in the sub-basins of the Eastern Himalayas. The maximum altitude of the eastern basins was high, but minimum altitude was comparatively low with respect to sub-basins located in Western and Central regions (Figure 3). This is the reason that overall snow area is expressed in lower percentage.

Interannual variability

Interannual variations of SCA over any region can be considered a good indicator of climatic variations. This study presents interannual variations of SCA in major basins of the H–K region, which is one of the most important mountainous cryospheric regions on Earth. Before we discuss our results, it will be pertinent to discuss a few studies by other research teams. For example, in the Indus basin, analysis of long datasets of precipitation from 1961 to 1999 showed statistically significant increases in winter and summer, and in the annual precipitation at several stations[40]. In a study using MODIS products from 2000 to 2011, SCA in the Indus basin showed a slight increasing trend[25]; however, it did not increase for the Ganga and Brahmaputra basins.

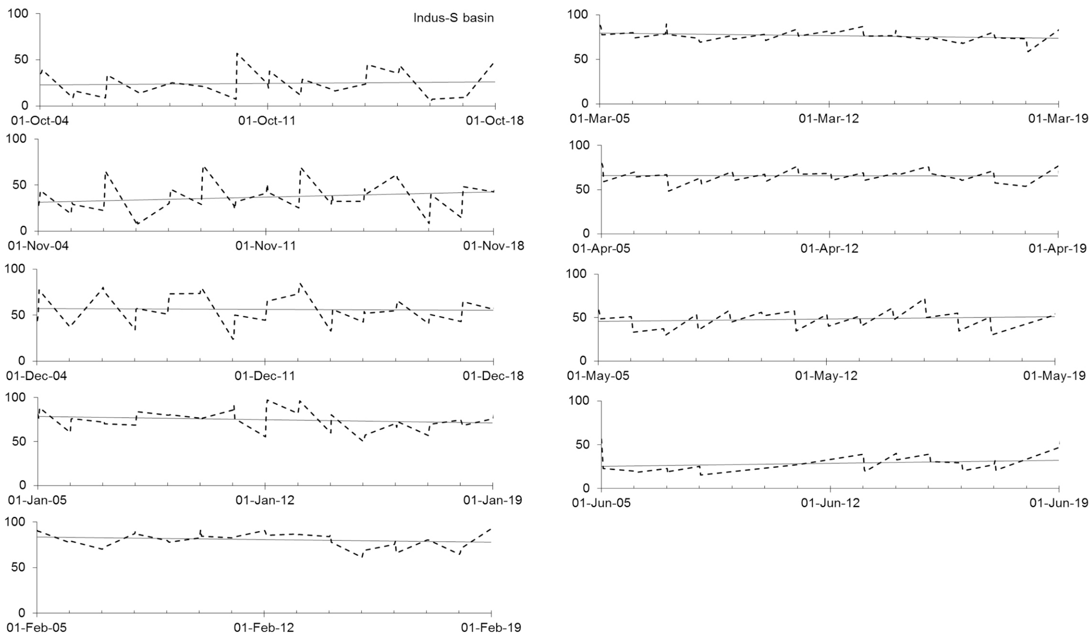

Figure 7. Monthly break-up of trends of snow area between 2004 and 2019 for the Indus–South sub-basins. Data for November show an increasing trend, while those for December–March show decreasing trend.

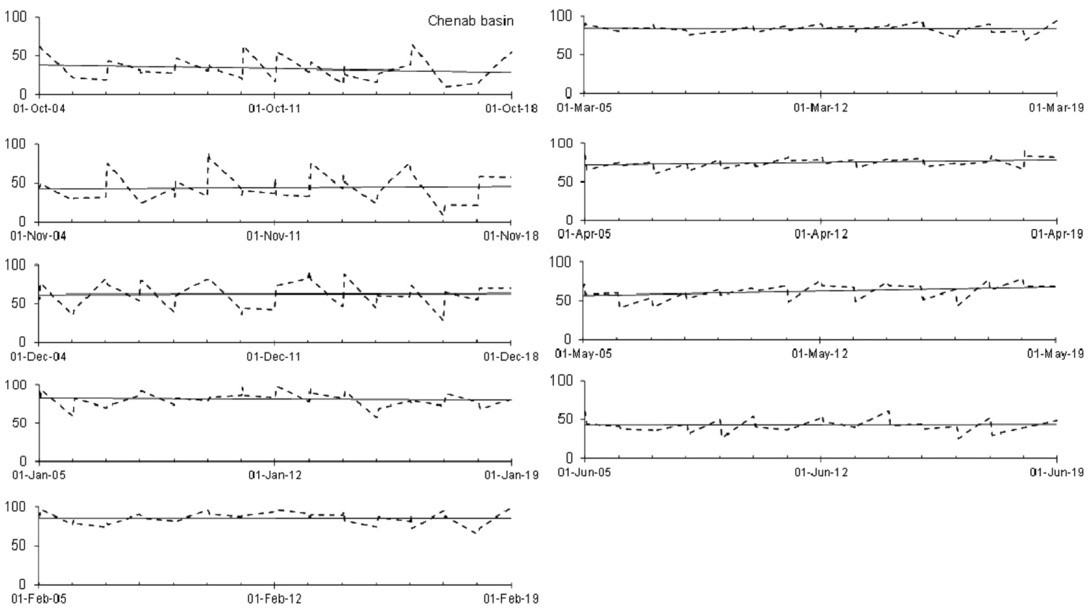

Figure 8. Monthly break-up of trends of snow area between 2004 and 2019 for the Chenab basin. Data for October show a slightly decreasing trend, while the rest show stable trend.

Snow parameters such as snow onset day, SCD, melt-out date and SCA were used to analyse spatio-temporal variability of snow cover over three decades using 1 km snow extent for the Alpine region, derived from AVHRR data over the period 1985–2011. On a regional scale, significant trends were found towards a shorter SCD at lower elevations in the southeast and southwest. No significant trend in the monthly mean SCA over the last 27 years was observed[41].

A study using MODIS snow cover products from 2000 to 2018 revealed that around 78% of the global mountain areas are undergoing a snow decline characterized by a decrease in snow cover duration up to 43 days, and snow cover area decrease up to 13% (ref. 26).

On the basis of bias-corrected GlobSnow 3.0 estimates, a different continental trend over the 39-yr satellite record was observed, with snow mass decrease by 46 gigatonnes per decade across North America, but a negligible trend

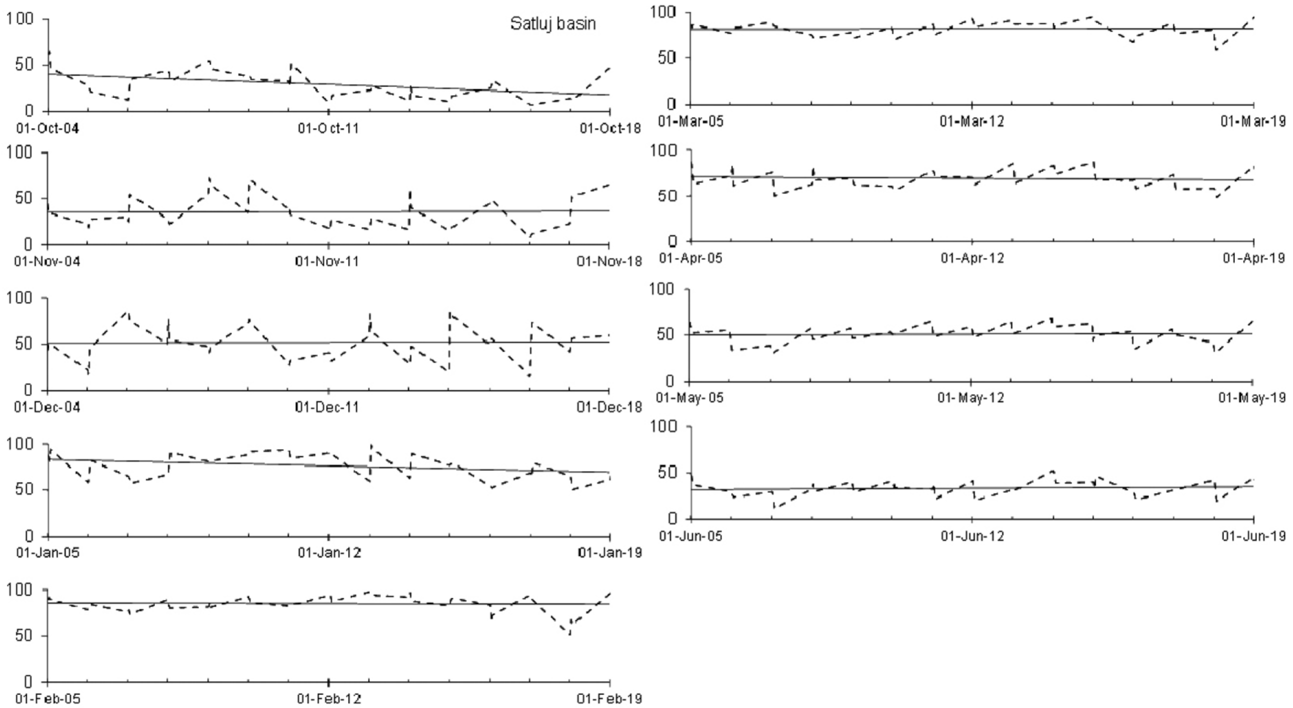

Figure 9. Monthly break-up of trends of snow area between 2004 and 2019 for the Satluj basin. Data for October and January show a decreasing trend, while the rest show stable trend.

across Eurasia; both continents exhibited high regional variability[23].

Trends in SCD were assessed using MODIS between 2002 and 2017 across the headwaters of primary river basins of the region (Amu Darya, Brahmaputra, Ganga, Indus and Syr Darya). Broadly, snow cover is in decline, which is most pronounced in the elevation bands where snow is most likely to be present and most needed to sustain the glaciers[42].

With respect to the aforementioned studies, we now compare our results of SCA analysis. SCA variations were generated by integrating the area of snow cover estimated for each sub-basin corresponding to the Indus–North group, Indus–South group, Chenab, Satluj, Ganga and Brahmaputra basins (Figure 5). An increase or decrease in snow area over 15 years was expressed through trend lines. Thus the trend lines in Figure 5 indicate no statistically significant increase or decrease in SCA based on Mann–Kendall test for all the basins. Variations are less in the Indus–North basin, which corresponds to the Karakoram region. If we compare these trends with the altitude of basins as shown in Figure 3, SCA remains the same irrespective of altitude. If the trends are compared with latitude based on the location of basins, they do not show any dependence overall, except for a little decline in the Satluj basin. In another study using AWiFS data over the period 2005–2016, SCA showed stability for 28 sub-basins located in the Western Himalaya[40]. The present study, which is an extension of our previous studies in terms of data, also shows similar observations and confirms the earlier findings.

We re-analysed the SCA data for accumulation months from October to March for the period between 2004 and 2019. Figures 6–11 show the monthly break-up of SCA trends for October to March separately. October and March experienced mild snowfall compared to November–February. The analysis was performed for all six basins. A decreasing pattern in snow area was observed over the Chenab, Satluj, Ganga and Brahmaputra basins for October. The outcome was different during different months for different basins. In the basins having their extent in lower latitudes, a decline in snow area was observed in the initial months of snowfall, as in the Satluj and Ganga basins.

Conclusion and future prospects

Monitoring of snow cover in the H–K region based on the analysis of ~35,910 snow products derived from AWiFS data since 2004 has revealed many facts useful for understanding hydrology and impact of climatic variations on snow cover extent. Latitudinal, longitudinal and altitudinal variations of the H–K mountains were reflected in the variability in accumulation of SCA. Variability of ablation was found to be less than in the accumulation period, indicating similar melting nature of snow across mountainous regions. The sub-basins on the right bank of the Indus or the northern side across the river (Karakoram

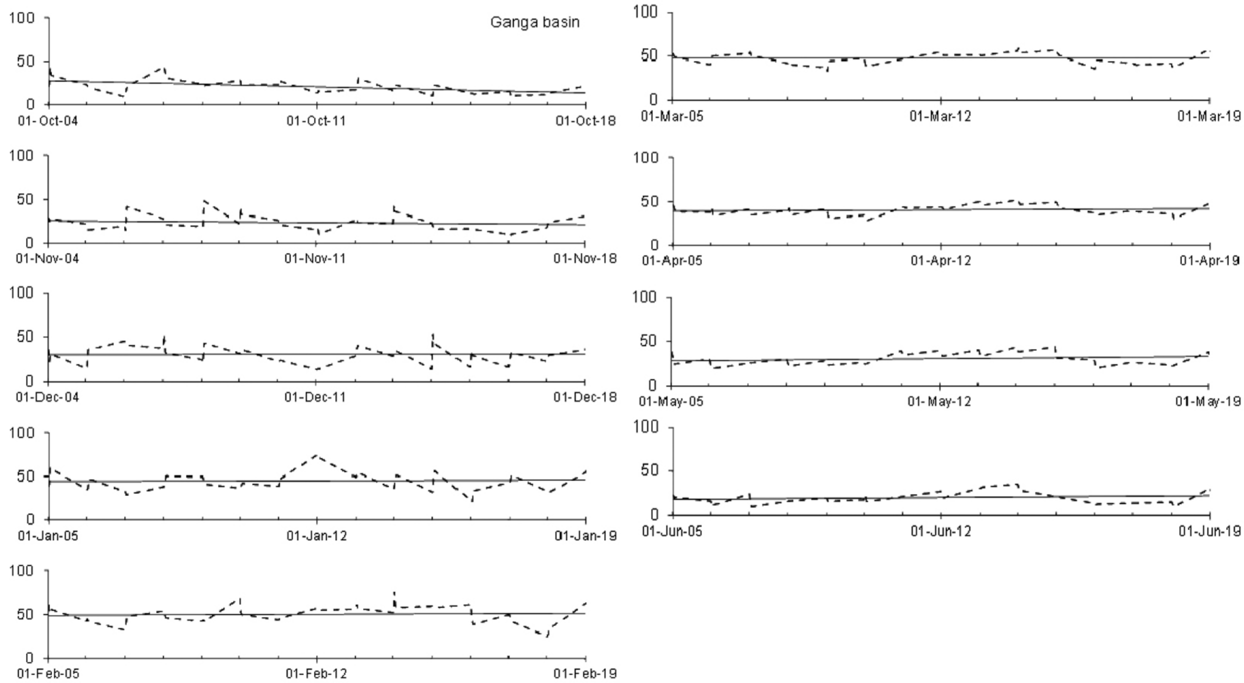

Figure 10. Monthly break-up of trends of snow area between 2004 and 2019 for part of the Ganga basin. Data for October show a decreasing trend, while the rest show stable trend.

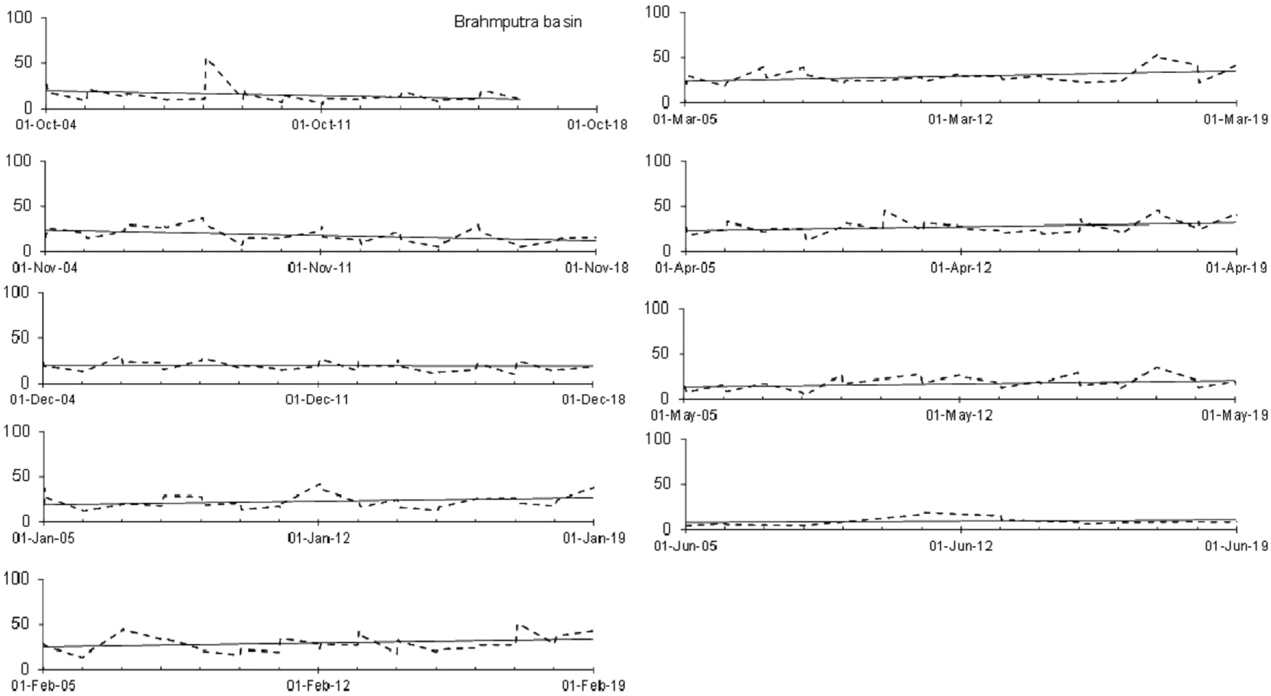

Figure 11. Monthly break-up of trends of snow area between 2004 and 2019 for part of the Brahmaputra basin. Data for October show a decreasing trend, while the rest show stable trend.

region) were covered with snow for most of the year, but comparatively less SCA was observed in other basins of the H–K region. Slopes of curves reflecting rate of accumulation and ablation differed for each basin. Mean of accumulation and ablation curves for each basin indicate that there is more variability in the accumulation part of snow precipitation than in ablation part. The ablation part governs the hydrology of the sub-basins. Higher percentage of SCA and the resulting higher load of snow accumulation in the Indus–North group of sub-basins for most of the year probably cause higher glacier sub-surface melting, thus accelerating ice movement. This is probably the reason for the Karakoram anomaly, with glaciers showing surging/advancement.

There was no statistically significant increase or decrease in snow area from Northwestern to Eastern Himalayas during the period of monitoring (2004–19). In spite of stable interannual trends in SCA, a slight declining trend in the early months of snow accumulation (October) and increase in subsequent months were observed in some sub-basins, indicating a delay in the onset of precipitation. This observation needs to be further substantiated. However, no change in SCA over the long term indicates the retreat of glaciers due to increased melting of glacier ice in summer, than due to lack of snow accumulation.

Snow area studies need to be conducted along with snow-depth studies to analyse the variation in snow mass. DEM differencing-based approaches, lidar-based techniques, microwave radiative transfer models using active radar data with penetration capabilities of radar and gravity-based methods will be useful to determine changes in the snow mass over a period of time. Though the present study does not indicate an overall decline in snow area in the H–K region, it indicates some decline in snow precipitation during the onset time.

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