

Evaluating snow cover changing trends of the Western Indian Himalaya

Seema Rani¹ 

Received: 15 September 2017/Revised: 9 December 2017/Accepted: 12 December 2017/Published online: 19 December 2017
© Korean Spatial Information Society 2017

Abstract The extent of snow cover in the Western Indian Himalaya determines the fluctuations in river discharge during the summer months and affects the water supply for hydroelectric generation, agriculture and related socio-economic systems which further affect the livelihood of the population in the area and downstream. Despite this importance, there is a lack of information about this region primarily due to the complexities of the processes involved in snow hydrology and the lack of snow cover and depth data in the high elevation areas. Periodical monitoring of the snow cover area (SCA) is an indispensable demand for short-term forecasts of the daily river flows and seasonal forecasts of run-off volume. Therefore, this study is an attempt to assess the annual, seasonal and monthly variations in the extent of snow cover of the Western Indian Himalaya. SCA was estimated using the MODIS/Terra Snow Cover 8-Day L3 Global 500 m (MOD10A2) data for the period 2000–2015. Monthly composite maps of SCA were prepared from 8 days composite snow cover area maps for the Kashmir, Himachal and Kumaon Himalaya. The study found a reduction in snow cover in the Indian Western Himalaya. The inter-seasonal variation in SCA was also observed in the study area. The study found an inter-regional variations in the extent of snow cover in the Western Indian Himalaya during the period of analysis. Emerging changes in the extent of snow cover would influence the availability of water in the near future.

Keywords Snow cover · Snow hydrology · MODIS · River discharge

1 Introduction

The Himalaya is covered by large areas of glaciers and permafrost. The largest rivers of Asia such as the Indus, Ganges and Brahmaputra drain from this region. The water availability in the area during the summer months determined by the extent of snow cover. It is not just significant for the downstream population, but likewise for the upstream population for several economic activities such as agriculture, hydro-power generation and domestic usage. The sustenance of the large population in India is influenced by fluctuations in the extent of snow cover in the Western Himalaya. Thus, analysis the spatial and temporal variability of snow cover area (SCA) is very important for various applications in the area.

According to the IPCC [1], the global combined land and ocean surface temperature indicates an increase of about 0.89 °C during 1901–2012. The evidences of warming were also found [1–5] in the Western Indian Himalaya and the rise in air temperature varied from 0.9 to 0.16 °C. The rising average air temperature is expected to affect the extent of snow cover and would have serious implication on the management of water resources in the region. SCA could be taken as an indicator to measure the climate variability in the Cryosphere [1, 6] as it is sensitive to the variations in air temperature. SCA changes would also determine the seasonal distribution of river flow [7]. These changes will have an influence on the availability of water throughout the year.

Limited meteorological stations in high altitude due to the rugged terrain and harsh climate limit the

✉ Seema Rani
seemarani.dse@gmail.com

¹ CSRD, Jawaharlal Nehru University, New Delhi 110067, India

meteorological data. In this condition, satellite remote sensing provide a useful tool for real-time and large spatial coverage for monitoring SCA over remote areas. Evidences of changes in snow cover area were found around the world. As a whole, Northern Hemisphere spring snow cover extent shows a considerable reduction over the past 90 years and the rate of decrease has been most rapid over the past 40 years. The estimated rates of reduction were found to be approximately $-3.24 \times 10^6 \text{ km}^2$ per 100 years for March and $-4.72 \times 10^6 \text{ km}^2$ per 100 years in April. These trends may be attributed to rising spring air temperatures over the mid-latitudes. The decline in SCA is evident in both March and April for Eurasia [8]. IPCC [5] highlighted that SCA in the Northern Hemisphere has been consistently below the 21 years (1974–1994) average since 1988. According to the latest report of IPCC [1], Northern Hemisphere annual SCA decreased about 10% since 1966, largely due to decreases in spring and summer SCA since the mid 1980s over both the Eurasian and American continents. Immerzeel et al. [9] concluded that the climate change has affected the Himalayan mountains, only the effects of climate change on water availability and food security differ substantially among basins in the Asia and cannot be extrapolated. Several studies [10–15] have also been made out along the Indian Himalaya to examine the changes in SCA by using remote sensing data (Landsat, IRS and MODIS). Gurung et al. [10] studied the changes in seasonal SCA in the Hindu Kush-Himalayan (HKH) region. He found the linear trend in annual snow cover during 2000–2010 of $-1.25 \pm 1.13\%$. A similar trend for Western, Central and Eastern HKH region is $8.55 \pm 1.70\%$, $+1.66 \pm 2.26\%$ and $0.82 \pm 2.50\%$, respectively. Snow cover trends over a decade were also found to vary seasonally in the region. Kulkarni [12] examined the seasonal snow cover of the Himalaya and showed large amounts of snow cover depletion in the former part of winter, i.e. from October to December.

Review of literature revealed that little work has been done to assess the changes in the SCA of the different states in the Western Indian Himalaya (WIH) with continuous latest remote sensing data. Study of SCA is also very important due to the fact that the changes in the snow cover area are closely associated with fluctuations in the climate variables. Thus, the present study is an attempt to assess the annual, seasonal and monthly trends in the SCA of the Kashmir, Himachal and a Kumaon region in the -Western Indian Himalaya during 2000–2015. The study would be helpful to manage the water resources and ensure environmental security in the WIH.

2 Study area

Western Indian Himalaya (WIH), covering the states of Jammu and Kashmir, Himachal Pradesh and Uttarakhand, bound by longitudes 72°E to 81°E and latitudes 28°N to 37°N (Fig. 1). It is known as Kashmir Himalaya (Jammu and Kashmir), Himachal Himalaya (Himachal Pradesh) and Kumaon Himalaya (Uttarakhand). The region covers a total area of 331,392 sq.km, which is about 10.08% of India's geographical area. Out of this, Kashmir Himalaya cover maximum area of about 6.7% and Kumaon Himalaya cover minimum area of about 1.62% area. WIH forms part of the Karakoram, Ladakh, Zaskar, Great Himalayan, Pirpanjal and Shiwalik ranges. Elevations in the region vary from a few hundred meters in the south to about 8500 m in the north. Slope of WIH is from north to south. Several sub-basins of both the Indus (Jhelum, Chenab, Shyok, Ravi, Sutlej and Gar Zangbo) and Ganges (Yamuna, Bhagirati and Alaknanda) forms part of this region.

Precipitation in the WIH occurs in the form of rain and snow, under the influence of western disturbances (October to May) and the south-west monsoon (July to September). Climatic conditions in WIH vary with the altitude. The average temperature in the southern foothills of WIH varies from about 30°C in summer to around 18°C in winter and in the middle WIH valleys, the average temperature is around 25°C in summer and the winters are really cold. On the higher region of the middle Himalaya, the temperature is recorded at around 15°C to 18°C in summer while the winters are below freezing point. Higher altitude areas of WIH of above 4800 m have temperature below freezing point and are permanently covered with snow.

3 Materials and methods

MODIS/Terra Snow Cover 8-Day L3 Global 500 m (MOD10A2) data for the period 2000–2015 was obtained from the Distributed Active Archive Center (DAAC), National Snow and Ice Data Center (NSIDC). The area is covered in the horizontal and a vertical tile number of h24v05. The MODIS uses 36 spectral bands with a spatial resolution of 250, 500 m and 1 km. MODIS also provides a grid of snow cover data at 500 m [16]. The accuracies and limitations of the MODIS terra, snow cover products have been explored with positive results [17–20]. Overall under a clear sky, the accuracy of MODIS Terra daily snow classification is over 90%.

MODIS satellite data have a high temporal resolution and has an automated snow-mapping algorithm, which reduces the time and errors incorporated during processing the satellite data manually. Each data granule contains the

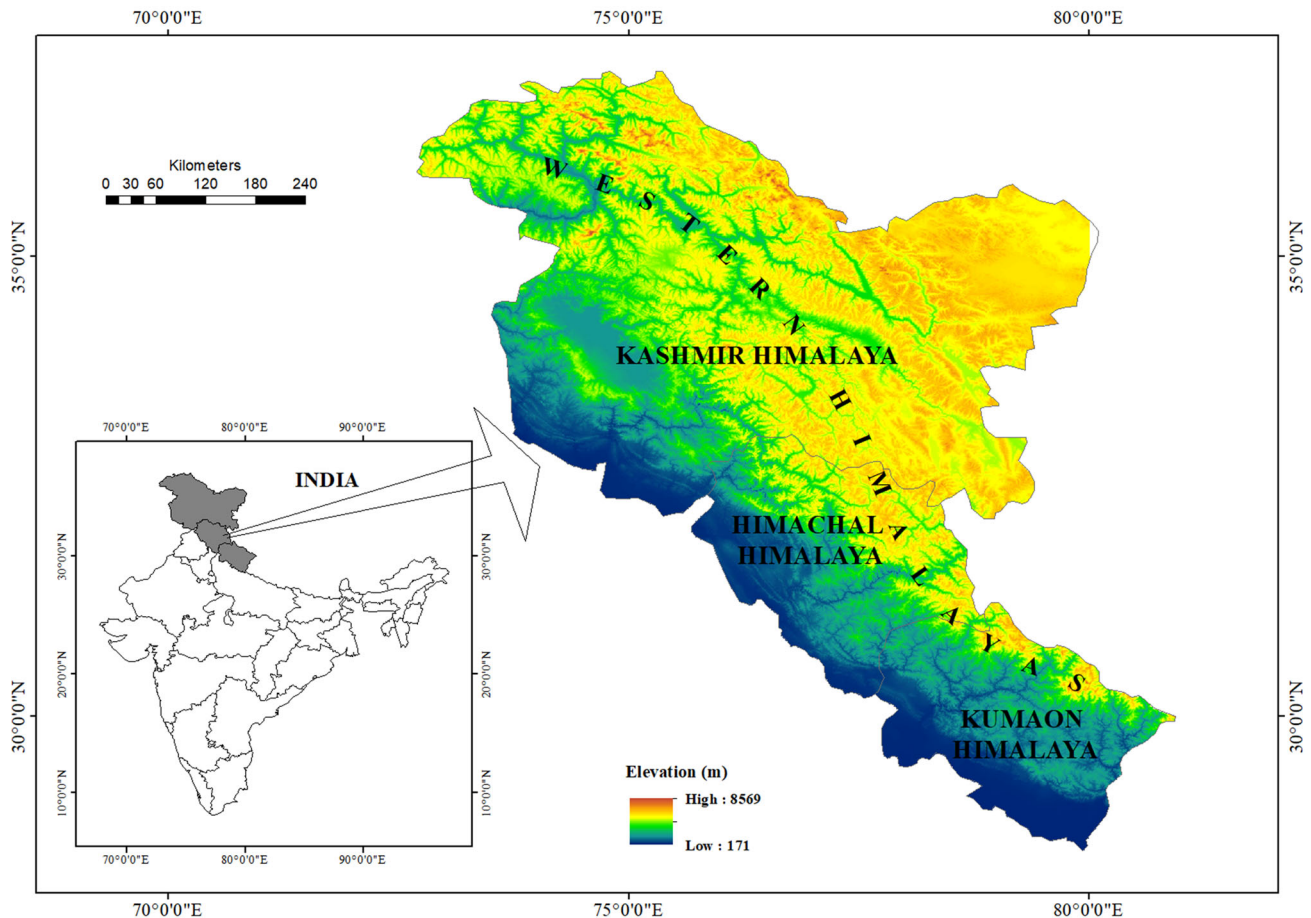


Fig. 1 Study area

two HDF-EOS local attribute fields (Maximum Snow Extent and 8 Day Snow Cover). The present study used maximum snow extent tile field data. This data is in compressed Hierarchical Data Format-Earth Observing System (HDF-EOS) format. HDF-EOS to Geo-TIFF Conversion Tool (HEG) was used for converting the HDF-EOS data to Geo-TIFF, native binary, or HDF-EOS grid format, reprojection of sinusoidal projection to Geographic Lat/Long and WGS84 datum and resampling to nearest neighbour.

MOD10A2 is based on the Normalized Difference Snow Index (NDSI). NDSI uses spectral characteristics of snow and is based on the concept of the Normalized Difference Vegetation Index (NDVI) used in vegetation mapping from remote sensing data [21, 22]. The MODIS/Terra MOD10A1 snow cover product is a classified image. For development of snow covered products, NDSI approach has been used to compute the snow cover area.

$$\text{NDSI} = \frac{(\text{Visible Band} - \text{SWIR Band})}{(\text{Visible Band} + \text{SWIR Band})}$$

or

$$\frac{(B4 - B6)}{(B4 + B6)}$$

The pixel values of the MOD10A1 data (snow cover daily tile field data) include 1 (no decision), 25 (snow-free land), 50 (cloud obscured), 200 (snow), and 254 (detector saturated) [23]. For MOD10A2, eight-day periods begin on the first day of the year and extend into the next year. It is based on overlay technique that is based on MAJORITY statistics. It determines the majority (cell value that occurs most often) of the inputs. The same technique was utilized for preparing monthly composite maps for all the regions from 8 days composite MODIS maps. ArcGIS 10.1 was utilized for preparing monthly composite maps of all the regions in WIH.

Descriptive statistics were used to characterize the SCA at monthly, seasonal and annual basis. The seasonal dynamics SCA pattern was studied using a scheme for seasons adapted from a previous work [24]. The seasons include winter (December to March), pre-monsoon season (April to June), monsoon season (July to September) and post-monsoon season (October and November). Ordinary

Table 1 Descriptive Statistics and Trend in mean annual SCA in Western Indian Himalaya during 2000–2015

Region	Mean (%)	SD (%)	CV (%)	Trend (%/year)
Western Himalaya	26.14	2.47	9.45	– 0.595*
Kashmir Himalaya	37.41	3.17	8.48	– 0.235
Himachal Himalaya	22.29	2.63	11.82	– 0.733**
Kumaon Himalaya	16.98	2.62	15.44	– 0.586*

SD standard deviation, CV coefficient of variation

Significant at *0.05 and **0.01 level

least-squares (OLS) regression test was used to assess the direction and magnitude of trend in the annual, seasonal and monthly SCA. The significance of the test is also computed [25]. The trend in the snow cover area is tested at both level of significance i.e. $\alpha = 0.01$ and 0.05 . The hypothesis that there is no trend is rejected when the computed t value is greater in absolute value than the critical value $t_{\alpha/2}$. Detailed SCA analysis was done for WIH and three sub regions (Fig. 1) to study inter-regional variation. Moreover, minority function of cell statistics in the ArcMap 10.2 was used to show the pattern of spatial variation in the snow cover area of the Western Himalaya during the study period. Minority function determines the value in a pixel that occurs least often of the inputs i.e. SCA. It helps to understand the inconsistency in the snow cover area of the Western Indian Himalaya during 2000–2015.

4 Results and discussions

4.1 Annual variations in SCA

Mean annual SCA observed for the WIH was 26.14% during 2000–2015 and the corresponding values of the Kashmir, Himachal and Kumaon Himalaya were 37.41, 22.29 and 16.98%, respectively (Table 1), indicating highest mean annual SCA in the Kashmir Himalaya during the period of analysis. Coefficient of variation (CV) of mean annual SCA of the WIH is 9.45% (Table 1), indicates low variation during the period 2000–2015. The corresponding values of sub-region level, indicate that the Kumaon Himalayan region has experienced highest variation in mean annual SCA during the period of analysis, compared to other regions (Table 1).

Annual variation in the SCA of the WIH was analyzed for the period 2000 to 2015 using average annual values (Fig. 2). A yearly average of SCA of the WIH varied from

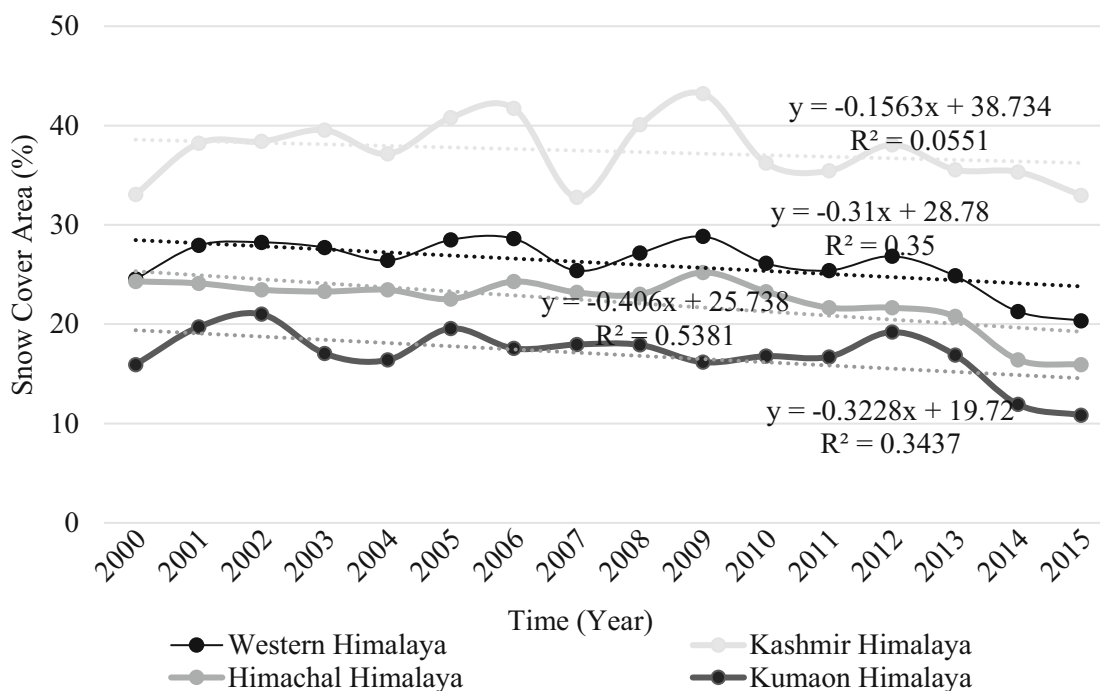


Fig. 2 Trends in the mean annual SCA of Western Indian Himalaya

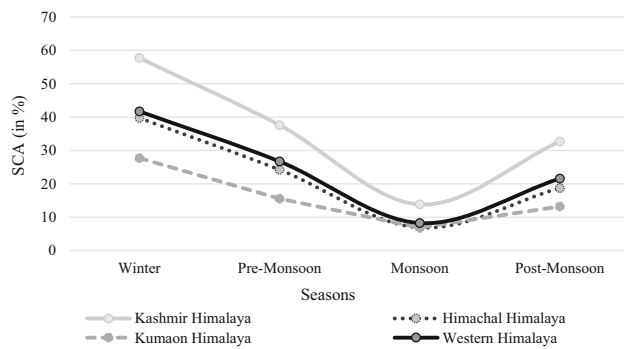


Fig. 3 Mean seasonal SCA during 2000–2015

20.4% in 2015 to 28.8% in 2009 (Fig. 2). Kashmir, Himachal and Kumaon Himalayan regions have also experienced lowest mean annual SCA in 2000 and the highest in within the concluding 5 years (Fig. 2). The analysis indicates a statistically significant decreasing trend in the mean annual SCA of WIH during 2000–2015 (Table 1). Himachal and Kumaon Himalayan regions also show a statistically significant decreasing trend in the mean annual SCA during the period of analysis. The magnitude of trend of mean annual SCA is highest in Himachal Himalaya ($-0.733\%/year$) followed by Kumaon and Kashmir Himalayan regions (Table 1). Gurung et al. [9] observed the similar trends in the mean annual SCA of the Western HinduKush Himalayan region for the period 2000–2010. Significant decreasing trends in the mean annual SCA in all the regions of WIH indicate the reduction in the extent of snow cover, that means more water would be available for use in the near future.

4.2 Seasonal variation in SCA

In the WIH, the maximum SCA of about 41.7% of the total area was observed during winter, followed by pre-monsoon (26.7%), post-monsoon (21.6%) and monsoon (8.2%) (Fig. 3). Kashmir, Himachal and Kumaon Himalayan regions also show similar observation in the seasonal SCA during the period of analysis (Fig. 3). This may be because monsoon is the season of abundant rain and snow and glaciers at very high altitudes continue melting during this season [23].

Table 2 SD and CV of mean seasonal SCA during 2000–2015

Season	Kashmir Himalaya		Himachal Himalaya		Kumaon Himalaya		Western Himalaya	
	SD (%)	CV (%)	SD (%)	CV (%)	SD (%)	CV (%)	SD (%)	CV (%)
Winter	4.5	7.9	5.1	12.7	5.9	21.1	4.5	10.7
Pre-monsoon	4.5	12.1	1.7	7.2	1.4	8.8	2.3	8.6
Monsoon	2	14.4	1.9	27.1	1.3	19.4	1.4	16.9
Post-monsoon	6.8	20.9	5.8	31	4.9	36.9	4.9	22.6

SD standard deviation, CV coefficient of variation

CV of seasonal SCA of the WIH indicates highest variation during the post-monsoon season (22.6%), followed by monsoon (16.9%), winter (10.7%) and pre-monsoon (8.6%) during the period 2000–2015 (Table 2). CV of SCA was computed for sub-regions of WIH for the period 2000–2015. CV values of SCA in the Kashmir Himalayan region indicate highest variation in the extent of snow during the post-monsoon season (20.9%) followed by monsoon (14.4%), pre-monsoon (12.1%, and winter (7.9%) during the period of analysis (Table 2). CV shows a dissimilar sequence of variation in the seasonal SCA of the Himachal Himalaya during the same period. Similarly, Kumaon Himalaya show highest variation in SCA during the post-monsoon (36.9%) followed by winter, monsoon and pre-monsoon (Table 2). However, least variation in the seasonal SCA in almost all the sub-regions was observed in pre-monsoon.

Trends in SCA of WIH, obtained for the individual seasons show a decreasing trend in all the seasons during 2000–2015, though the trend is significant during winter (Table 3; Fig. 4). The magnitude of the trend in the SCA is highest during the winter and least in pre-monsoon. Similar trends in the SCA are being observed in the Kashmir Himalaya during the period of analysis (Table 3 and Fig. 4). Himachal Himalaya has experienced a decreasing trend in SCA during all the seasons during 2000–2015 (Table 3; Fig. 4) and the trend in winter and post-monsoon SCA is statistically significant (Table 3). The results are not consisted with the findings of the study, done in the Western Hindu-Kush Himalaya for the period 2000–2010 [9] that shows a declining trend in the SCA in the pre-monsoon for Hindu Kush Himalaya (HKH) region ($-1.04 \pm 0.97\%$), primarily due to inter-annual variations in circulation patterns. They found rising trends in all the seasonal snow cover areas of the Western HinduKush Himalaya (HKH) region. The reason could be the different time period of study. Kumaon Himalaya has also experienced a decreasing trend in SCA during the all the seasons (Table 3; Fig. 3), though the magnitude of the trend in highest during the winter season ($-0.643\%/year$) (Table 3).

Singh and Kumar [26] noticed that snow and glacier melt runoff cause an earlier response of total stream flow

Table 3 Trend (%/year) in mean seasonal SCA during 2000–2015

Season	Kashmir Himalaya (%/Year)	Himachal Himalaya	Kumaon Himalaya	Western Himalaya
Winter	- 0.577*	- 0.836**	- 0.643**	- 0.796**
Pre-monsoon	0.006	- 0.04	- 0.022	- 0.11
Monsoon	0.224	- 0.169	- 0.198	- 0.151
Post-monsoon	- 0.182	- .527*	- 0.395	- 0.426

Significant at *0.05 and **0.01 level

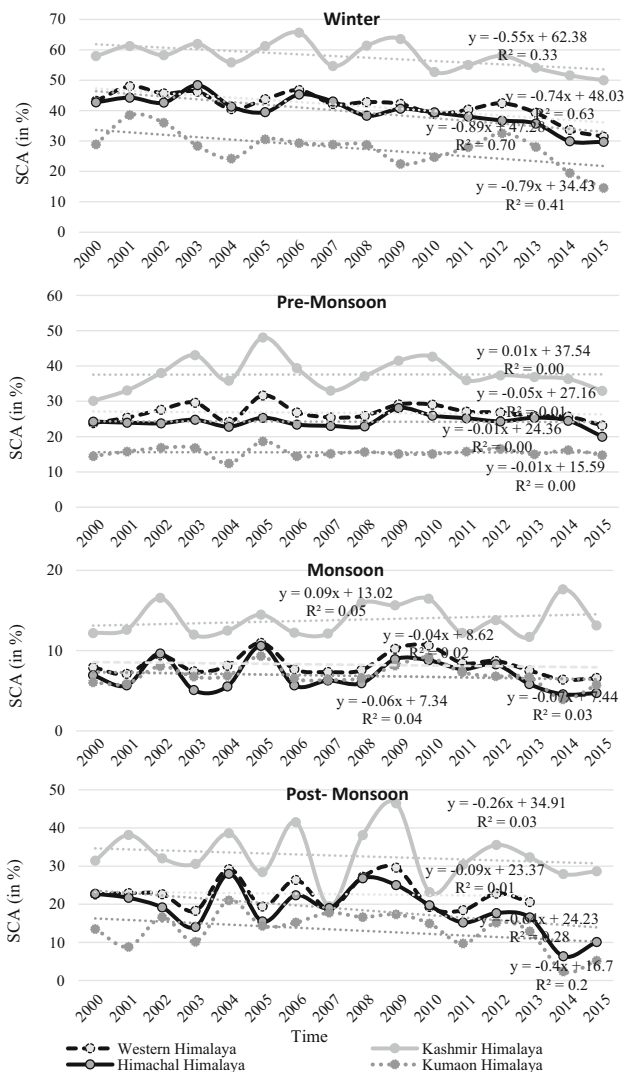


Fig. 4 Trend in mean seasonal SCA of the Western Indian Himalaya

and a change in flow distribution under a warmer climate scenario. Total stream flow indicates that an increase in air temperature produces an increase run-off in the pre-monsoon followed by an increase in run-off during the monsoon. Singh and Bengtsson [27] examined the impact of a warmer climate on rainfall fed, snow fed and glacier fed river basin of Himachal Pradesh and found that a warmer

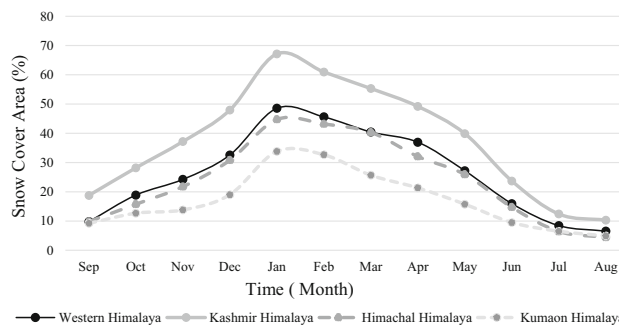


Fig. 5 Snow accumulation and ablation curve during the period 2000–2015

climate would result in water availability reduction in the snow fed basins due to a compound effect of increase in evaporation and decrease in melt (due to availability of lesser amount of snowfall in the catchment area) whereas from the glacier fed basin it increased.

4.3 Monthly variations in SCA

According to the average monthly SCA of WIH of all the months for the period 2000–2015, snow starts to accumulate from late-October to mid-March and begins to decline from April to end of August (Fig. 5). Average snow cover reaches a maximum point in February to about 45.6% of the entire field and proceeds to melt till August. In August, snow extent remains about 6.5%. The analysis revealed an inter-regional variations in the percentage of monthly SCA. It may be attributed to variation in the climatic conditions and topography [14].

Coefficient of variation of the SCA of the Western Indian Himalaya, indicates highest variation from September to December and least during February during the period of analysis (Table 4). Mean monthly SCA of the Kashmir and Himachal Himalaya show high variation in September. Results of coefficient of variability indicate that SCA is more steady during the winter months than other seasons during 2000–2015. Though, monthly trend analysis of the SCA of the WIH shows a significant reduction during all the months during 2000–2015 (Table 5). In Kashmir Himalaya, the SCA has shown a

Table 4 Descriptive statistics of mean monthly SCA during 2000–2015

Months	Kashmir Himalaya			Himachal Himalaya			Kumaon Himalaya			Western Himalaya		
	Mean (%)	SD (%)	CV (%)	Mean (%)	SD (%)	CV (%)	Mean (%)	SD (%)	CV (%)	Mean (%)	SD (%)	CV (%)
Jan	67.1	3.5	5.3	44.7	4.7	10.4	33.8	10	31	48.6	4.8	9.9
Feb	61	4.7	7.7	43.2	4.2	9.7	32.7	6	18	45.6	3.8	8.3
Mar	55.3	5.2	9.4	40.3	5.6	13.8	25.7	7.5	29	40.4	5.4	13.4
Apr	49.2	5.3	11	32.1	3	9.2	21.3	2.1	9.6	37	3.7	9.9
May	39.9	6.6	17	25.9	2.8	10.9	15.8	2.2	14	27.2	3.3	12.2
Jun	23.7	5.5	23	14.7	3	20.6	9.5	1.9	20	16	2.8	17.7
Jul	12.4	2.6	21	6.4	2.2	34.4	6.5	1.7	27	8.4	1.8	21.2
Aug	10.3	1	9.8	4.4	1.4	31.3	4.9	1.8	36	6.5	1.2	17.8
Sep	18.8	5.4	29	9.8	3.8	38.8	9.2	3.3	36	9.8	2.4	24.7
Oct	28.2	7	25	15.7	6.4	40.6	12.7	5.2	41	18.9	5.3	28.2
Nov	37.2	9.5	26	21.8	7.7	35.3	13.8	5.2	38	24.2	6.3	25.8
Dec	48	11.5	24	30.8	10.9	35.4	19	7.8	41	32.6	9.1	27.8

SD standard deviation, CV coefficient of variation

Table 5 Trend (%/year) in mean monthly SCA during 2000–2015

Months	Kashmir Himalaya (%/year)	Himachal Himalaya	Kumaon Himalaya	Western Himalaya
Jan	– 0.512	– 0.770**	– 0.416	– 0.671**
Feb	– .670**	– 0.730**	– 0.516*	– 0.818**
Mar	– 0.433	– 0.777**	– 0.696**	– 0.725**
Apr	– 0.508*	– 0.752**	– 0.496	– 0.730**
May	0.296	0.049	0.146	0.241
Jun	0.15	0.619*	0.324	0.394
Jul	0.106	0.013	0.411	0.186
Aug	– 0.198	0.072	– 0.327	– 0.194
Sep	0.232	– 0.282	– 0.282	– 0.313
Oct	– 0.005	– 0.163	– 0.348	– 0.18
Nov	– 0.258	– 0.662**	– 0.393	– 0.509*
Dec	– 0.387	– 0.605*	– 0.45	– 0.533*

Significant at *0.05 and **0.01 level

significant decreasing trend in February and April. SCA of Himachal Himalaya has shown a significant decreasing trend in winter and post monsoon months. In Kumaon Himalaya, trend analysis indicates a significant decreasing trend in SCA of February and March. The variation in the SCA may be attributed to changes in the air temperature and form of precipitation as these two factors determine the rate of snow accumulation and ablation.

4.4 Inconsistency in spatial pattern of SCA

Inconsistency in the SCA of all the months in the Western Indian Himalaya during 2000–2015 is shown in Fig. 6. It shows the areas in the maps where extent of snow is not

frequent during the study period. It further indicates that all months have high inconsistent area of snow cover except monsoon months during the study period (Fig. 6). Among winter months, high inconsistency in SCA is observed from January to March over the years whereas low inconsistency is observed in SCA from June to August during the study period.

5 Conclusions

The present work is an effort to assess the annual, seasonal and monthly movements in the SCA of the Western Indian Himalaya and its sub regions (Kashmir, Himachal and

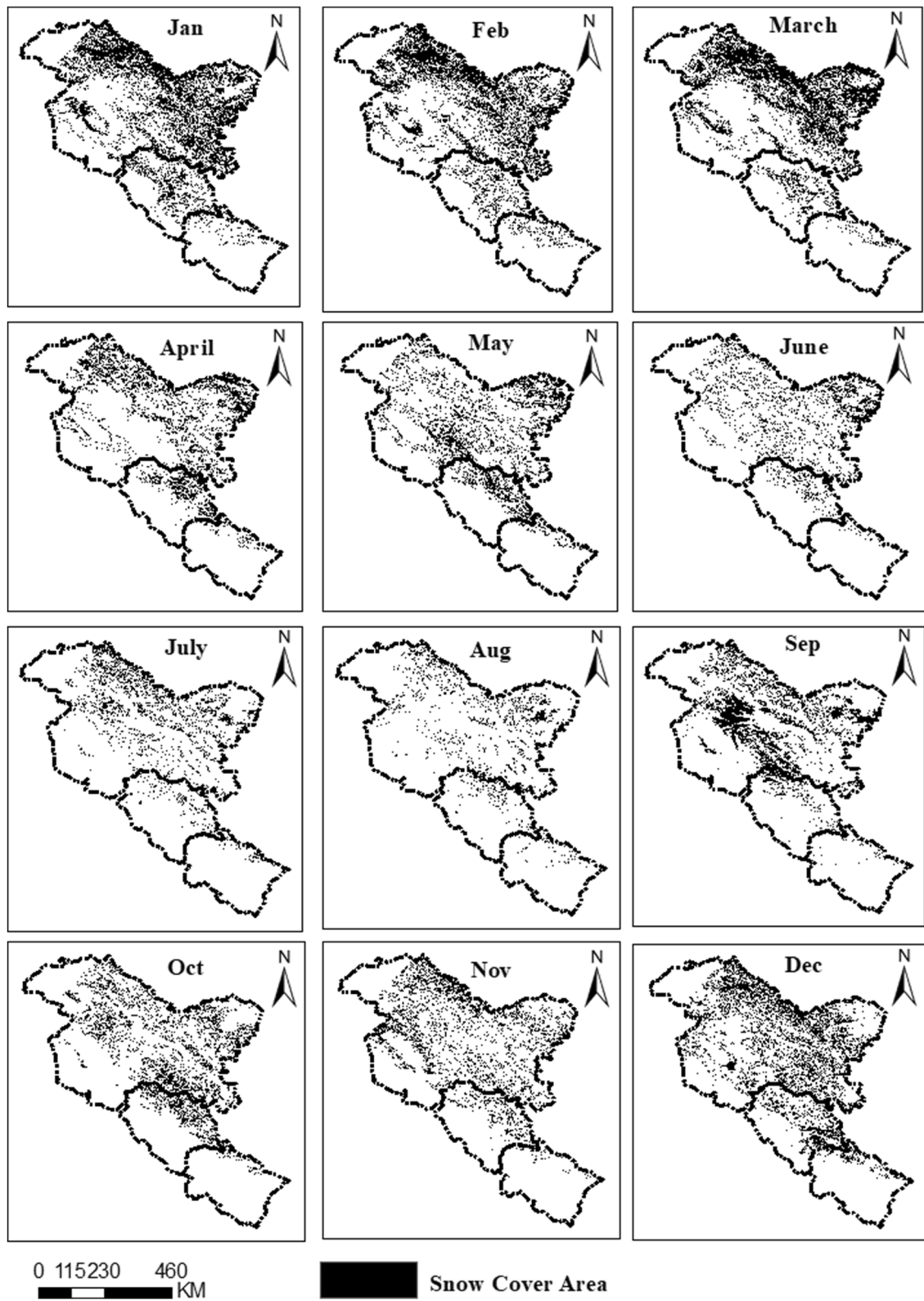


Fig. 6 Inconsistency in mean monthly SCA in Western Indian Himalaya during 2000–2015

Kumaon Himalaya) for the period 2000–2015 by using MOD10A2 data.

Annual trend analysis indicates a decreasing trend in the mean annual SCA of WIH during 2000–2015. In sub regions, Kashmir, Himachal and Kumaon Himalayan regions indicate a similar tendency in the mean annual SCA during the period of analysis and the magnitude of the trend is highest in Himachal Himalaya ($-0.733\%/year$) and least in the Kashmir Himalaya.

Seasonal trend analysis of SCA of WIH, obtained for the individual seasons indicates a decreasing tendency in all seasons during 2000–2015, though the result is significant in winter and it also showed the highest magnitude of change. At sub regional level, similar seasonal trend in the SCA was being observed in the Himachal and Kumaon Himalaya during the period of analysis. In contrast, Kashmir Himalaya has experienced a decreasing trend in SCA during winter and post monsoon only.

The monthly trend analysis of SCA of the WIH shows a decreasing trend in almost all the months during the period 2000–2015. In Kashmir Himalaya, SCA has shown a significant decreasing trend in February and April. SCA in Himachal Himalaya has shown a significant decreasing trend from January to April and November–December. In Kumaon Himalaya, trend analysis indicates a significant decreasing trend in SCA in February and March. The variation in the snow cover area may be attributed to changes in the air temperature and form of precipitation as these two factors determine the rate of snow accumulation and ablation at different altitudes. The study would be helpful to policy makers for managing the water resources in the region.

Acknowledgements Author is very grateful to the National Snow and Ice Data Center (NSIDC) for sharing the Moderate Resolution Imaging Spectro-radiometer (MODIS) data in the public domain.

References

1. IPCC. (2013). *Climate change 2013: The physical science basis, contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)*. Cambridge: Cambridge University Press.
2. Bhutiyani, M., Kale, V., & Pawar, N. (2007). Long-term trends in maximum, minimum and mean annual air temperatures across the north western Himalaya during the twentieth century. *Climate Change*, 85(1–2), 159–177.
3. Dash, S., Jenamani, R., Kalsi, S., & Panda, S. (2007). Some evidence of climate change in twentieth-century India. *Climatic Change*, 85(3–4), 299–321.
4. Islam, Z.-U., Rao, L., Zargar, H., Ahmad, S., & Khan, M. (2008). Temperature variability in Himalaya and threat to the glaciers in the region: A study aided by remote sensing and GIS. *Journal of Environmental Research and Development*, 3(2), 495–505.
5. Dimri, A. P., & Dash, S. (2012). Wintertime climatic trends in the Western Himalaya. *Climatic Change*, 111(3–4), 775–800.
6. IPCC. (2007). *Climate change 2007: Impacts, adaptation and vulnerability*. In M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, & C. E. Hanson (Eds.), *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.
7. IPCC. (1996). *Climate change 1995: The IPCC Scientific Assessment, contribution of Working Group I To Second Assessment Report of Intergovernmental of Climate Change (IPCC)*. Cambridge: Cambridge University Press.
8. Brown, R. (2000). Northern Hemisphere snow cover variability and change, 1915–97. *Journal of Climate*, 13, 2339–2355.
9. Immerzeel, W., van Beek, L., & Bierkens, M. (2010). Climate change will affect the Asian water towers. *Science*, 328, 1382–1385.
10. Gurung, D., Kulkarni, A., Giriraj, A., Aung, K., Shrestha, B., & Srinivasan, J. (2011). Changes in seasonal snow cover in Hindu Kush-Himalayan region. *The Cryosphere Discussions*, 5, 755–777.
11. Jain, S., Rathore, D., & Chaudhry, A. (2001). *Snow cover estimation in Himalayan basins using remote sensing*. Roorkee: A Report by the National Institute of Hydrology.
12. Kulkarni, A. (2010). Monitoring Himalayan Cryosphere using remote sensing techniques. *Journal of the Indian Institute of Science*, 90(4), 457–469.
13. Kulkarni, A., Mathur, P., Rathore, B., Alex, S., Thakur, N., & Kumar, M. (2002). Effect of global warming on snow ablation pattern in Himalaya. *Current Science*, 83(2), 120–123.
14. Negi, H. S., Thakur, N. K., Kumar, R., & Kumar, M. (2009). Monitoring and evaluation of seasonal snow cover in Kashmir valley using remote sensing. *GIS*, 6, 711–720.
15. Sharma, V., Mishra, V. D., & Joshi, P. K. (2014). Topographic controls on spatio-temporal snow cover distribution in Northwest Himalaya. *International Journal of Remote Sensing*, 35, 37–41.
16. Hall, D., Riggs, G., Salomonson, V., DiGirolamo, E., & Bayr, J. (2002). MODIS snow-cover products. *Remote Sensing Environment*, 83, 181–194.
17. Chelamallu, H., Venkataraman, G., & Murti, M. (2013). Accuracy assessment of MODIS/Terra snow cover product for parts of Indian Himalaya. *Geocarto International*, 29, 592–608.
18. Hall, D., & Riggs, G. (2007). Accuracy assessment of the MODIS snow products. *Hydrological Processes*, 21, 1534–1547.
19. Jain, S., Goswami, A., & Saraf, A. (2008). Accuracy assessment of MODIS, NOAA and IRS data in snow cover mapping under Himalayan conditions. *International Journal of Remote Sensing*, 29(20), 5863–5878.
20. Klein, A., & Barnett, A. (2003). Validation of daily MODIS snow cover maps of the Upper Rio Grande River Basin for the 2000–2001 snow year. *Remote Sensing of Environment*, 86(2), 162–176.
21. Hall, D., Riggs, G., & Salomonson, V. (1995). Development of methods for mapping global snow cover using moderate resolution imaging spectrometer (MODIS) data. *Remote Sensing Environment*, 4, 127–140.
22. Gupta, R., Haritashya, U., & Singh, P. (2005). Mapping dry/wet snow cover in the Indian Himalaya using IRS multispectral images. *Remote Sensing Environment*, 97(4), 458–469.
23. Hall, D., Riggs, G., & Salomonson, V. (2007). *updated daily MODIS/aqua snow cover daily L3 global 500 m grid*. Boulder, CO: National Snow and Ice Data Center, Digital media.
24. Jain, S., Goswami, A., & Saraf, A. (2009). Role of elevation and aspect in snow distribution in Western Himalaya. *Water Resource Management*, 23, 71–83.
25. Onoz, B., & Bayazit, M. (2003). The power of statistical tests for trend detection. *Turkish Journal of Engineering and Environmental Sciences*, 27, 247–251.

-
26. Singh, P., & Kumar, N. (1997). Impact assessment of climate change on the hydrological response of a snow and glacier melt runoff dominated Himalayan River. *Journal of Hydrology*, *193*, 316–350.
27. Singh, P., & Bengtsson, L. (2005). Impact of warmer climate on melt and evaporation for the rainfed, snowfed and glacierfed basins in the Himalayan region. *Journal of Hydrology*, *300*, 140–154.