Trends of snow cover in Western and West-Central Himalayas during 2004–2014

B. P. Rathore[1,*], I. M. Bahuguna[1], S. K. Singh[1], R. M. Brahmbhatt[2], S. S. Randhawa[3], P. Jani[4], S. K. S. Yadav[5] and A. S. Rajawat[1]

[1]Space Applications Centre (ISRO), Ahmedabad 380 015, India
[2]M. G. Science Institute, Ahmedabad 380 009, India
[3]State Centre on Climate Change, SCSTE, Shimla 171 009, India
[4]CEPT University, Ahmedabad 380 009, India
[5]Remote Sensing Applications Centre, Lucknow 226 021, India

The extent of snow cover on the earth is considered an important parameter for numerous climatological and hydrological applications. Snow cover dynamics in mountainous regions is a vital input for energy balance, glacier mass balance, climate change and snowmelt runoff modelling. There have been global efforts for monitoring of snow cover of earth at varying spatial and temporal scales by generation of snow products. Among these, one of the high temporal and spatial resolution datasets has been generated using advanced wide field sensor data for Western and West-Central Himalayan region at the Space Applications Centre, Ahmedabad. This is done using an algorithm developed based on normalized difference snow index. This paper discusses the trends of snow cover from 2004 to 2014 based on an input of approximately 12,600 snow cover products at sub-basin scale in Indus, Chenab, Satluj and Ganga basins. Analysis of snow cover shows high variability during accumulation than in ablation period. A subtle increase in snow cover was observed in all basins during 2004–2014.

Keywords: Ablation, accumulation, AWiFS, snow cover, NDSI, Western and West-Central Himalaya.

Introduction

OCCURRENCE and distribution of snow cover on the earth's surface is largely governed by altitude and latitude of a specific region. In terms of the spatial extent, snow cover is the second largest component of the cryosphere and covers approximately 40–50% of the earth's land surface during Northern Hemisphere winter[1–3]. It is used as an important parameter in radiative budget studies as the surface reflection of incoming solar radiation from the snow surface forms an important component of the surface energy balance[4–6]. Snow cover exhibits a major influence on the earth's radiation balance during spring (April–May) when the incoming solar radiation is maximum. The higher albedo from 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. Therefore, it keeps earth's radiation budget in balance as it reflects a large portion of the insolation[7–10].

Snow precipitation also plays an important role in feeding the glaciers and ice sheets of the world. Annual precipitation of snow feeds the accumulation zone of the glaciers and is considered an important parameter for glacier mass balance studies. It is used as an important hydrological parameter in the snowmelt runoff estimation. Snowmelt is the source of freshwater required for drinking, domestic, agricultural, hydropower and industrial sectors especially in middle and high latitudes[9,11–13]. One of the vital applications of snow cover measurements is in climate change studies. Intra-annual accumulation and ablation patterns and inter-annual trends of snow cover are analysed to understand the impact of climatic variations[14–16]. All the aforementioned applications of snow cover necessitate a regular generation of database of snow cover. This is possible only by means of earth observation satellites.

Since a part of Himalayan region also receives snow precipitation annually specially in winters, and throughout the year at high altitudes, generation of snow cover data and its analysis is of prime importance to the nation. Almost 30–50% of annual flow of all the rivers originating from higher Himalayas comes from its snow-melt runoff[17,18]. It is with this view that a continued programme of generation of snow cover products covering almost the entire Indian Himalayan region is on at the Space Applications Centre, ISRO, Ahmedabad. The present study discusses the analysis of variability of areal extent of snow in Western and West-Central Himalaya for consecutive ten years from 2004 to 2014. It covers areas partly under Indus and Ganga basins. Indus basin in Indian region covers areas north and south of Indus river in Kashmir-Karakoram, areas under the catchment of Sutlej and Chenab in Himachal Pradesh and Jammu and Kashmir

*For correspondence. (e-mail: rathorebp@sac.isro.gov.in)

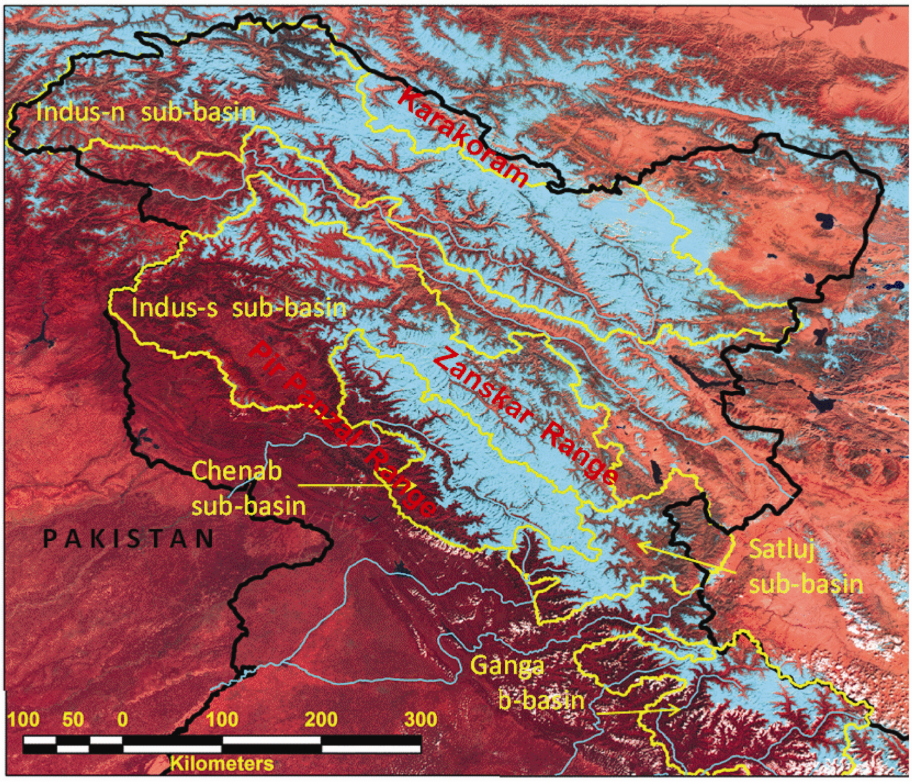

Figure 1. Location map of Indus-N, Indus-S, Chenab, Satluj and Ganga basins of Western and West-Central Himalayan region.

(J&K). Areas under Ganga basin cover Uttarakhand region (Figure 1). These regions cover a vast geographical expanse in terms of altitude and location, and are therefore subject to different geomorphological–climatological set-up governing the amount of snow precipitation.

Data used and methodology

The database generated and reported here for the analysis of snow cover in Western and West-Central Himalayan region is based on digital multi-spectral and temporal data acquired by advanced wide field sensor (AWiFS) sensors onboard Resourcesat-1 and -2 satellites of Indian Remote Sensing satellite series launched in October 2003 and 2011 respectively. AWiFS has three bands in visible and near infrared (VNIR) and one band in SWIR of electromagnetic spectrum. This sensor has a spatial resolution of 56 m. The radiometric quantization of Resourcesat 1 AWiFS is 10-bit and its successor is 12-bit. It covers a swath of 740 km. It is for this reason that a trend analysis has been carried out from 2004 to 2014. Resourcesat 2 has a follow-up as Resourcesat 2A launched in April 2016. Therefore, this trend analysis will also continue in future to archive a strong climatic database. Its wide swath produces a repeativity of 5 days. Its spatial resolution of 56 m and 5 days repeativity makes it one of the most useful sensors available globally for snow cover extraction. The high radiometric quantization does not saturate the sensor over snowy regions.

Snow cover extraction involves two major steps – georeferencing of data and execution of an algorithm to extract snow cover. Georeferencing is carried out by creating a master image of AWiFS data of the study area using reference points from rectified Landsat TM data. Then snow is extracted from AWiFS by executing an algorithm based on normalized difference snow index (NDSI)[1,19,20]. NDSI is derived by finding the ratio of difference and sum of reflectance in green (B2) and SWIR (B5) bands. Reflectances are derived using a well-established relationship involving sensor parameters, irradiance and radiance reaching the sensor. In fact, inclusion of SWIR band has been the key factor in the development of NDSI-based algorithm for AWiFS sensor. NDSI based algorithm is executed on each AWiFS scene. In this algorithm NDSI values >0.4 are used to extract snow cover.

Two types of products are generated i.e. one at 5-day repeativity and the other at 10-days. For 10 day products, a composite mean of three consecutive 5-day products is generated. NDSI does not differentiate water and snow pixels as, in SWIR band, both have high absorption features. Therefore, a mask is generated around water pixels.

After generating a snow product for the entire scene, a subset is created as per the area required to be monitored.

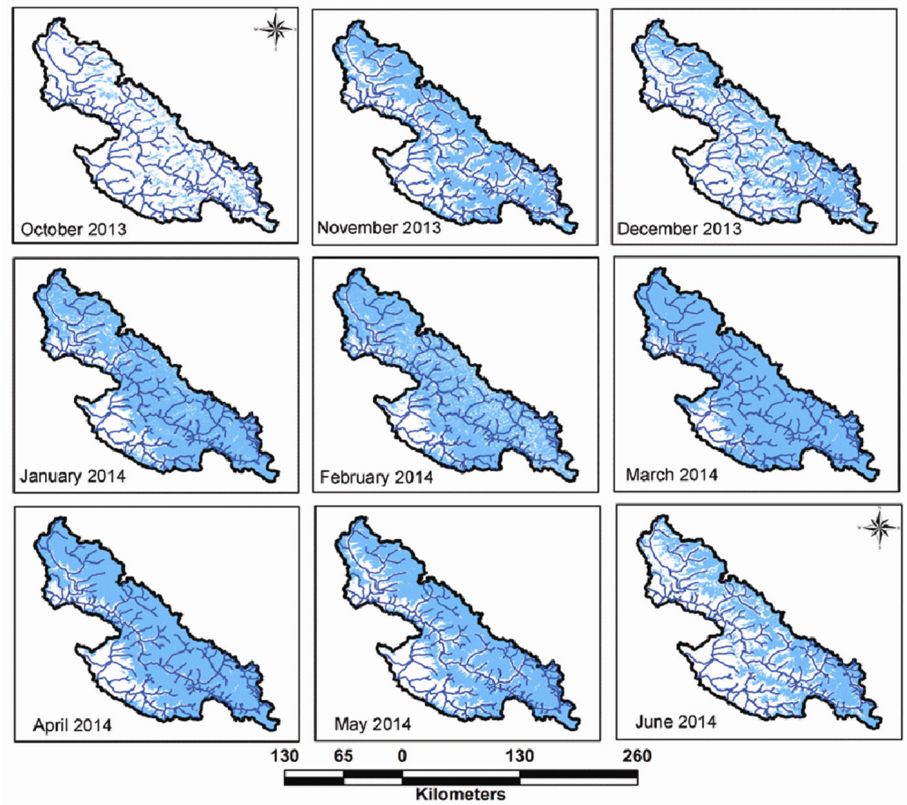

Figure 2. Snow cover map of Chenab basin for the year 2013–14.

Here, our area of interest is 28 small river sub-basins in the range 1096–27,120 sq. km. These sub-basins are part of Indus, Chenab, Satluj and Ganga basins. Though Chenab and Satluj basins are tributary basins of Indus, both have been treated separately for snow cover analysis as their area is very large. Thus, Indus basin excludes Chenab and Satluj. Since Indus basin minus Satluj and Chenab still covers a very large area, it has been further bifurcated as north and south separated by east to west flowing Indus river. In the present study, Indus-North (Indus-N) comprises 6 sub-basins (Nubra, Shyok, Shigar, Shasgan, Hanza and Gilgit), Indus-South (Indus-S) comprises 7 sub-basins (Jhelum, Kishanganaga, Astor, Suru, Dras, Shigo and Zanskar), Satluj comprises 6 sub-basins (Beas, Parbati, Jiwa, Baspa, Pin and Spiti), Chenab comprises 6 sub-basins (Chandra, Bhaga, Miyar, Bhut, Warwan and Ravi) and Ganga comprises 3 sub-basins (Alaknanda, Bhagirathi and Yamuna). The snow products of these sub-basins have been integrated for the above five large river basins. Figure 2 shows an example of snow cover products of Chenab basin for the year 2013–14.

The algorithm used in this study was developed and validated over a rugged terrain of Himalayan region[19] with assessment of snow pixel map accuracies using spectro-radiometer data of different objects, field verifications over identified locations and over different land cover classes[14]. The spatial resolution of AWiFS sensor showed better estimation of snow patches than moderate resolution imaging spectro radiometer (MODIS)[15]. A comparative analysis of snow products of Bhaga sub-basin (Himachal Pradesh) was carried out before and after topographic correction (orthorectification)[13]. A less than 1% variation was observed. This study deals with the relative variation of snow cover area in spatial and temporal domains and not with absolute snow cover.

From the snow cover statistics, snow cover trends were drawn. To evaluate the statistical significance of snow cover trends, Mann–Kendall test was performed. The snow cover was further analysed with respect to area-altitude distribution. For this analysis, altitude zones of 500 m were made by overlaying the contours which were derived from shuttle radar topography mission (SRTM) digital elevation model (DEM) in ARC GIS platform. The DEM product has 90 m spatial resolution and vertical root mean square error of 16 m (ref. 21). Hypsographic curves were prepared to estimate snow cover area covered in some definite altitude zones. The curves were also used to find the altitude of snow line. Table 1 shows the hypsographic analysis results used to derive snow line altitude. The altitude varies from 1000 to 7000 m for all basins. To check the relationship of snow cover with air temperature, a data of maximum and minimum temperature of ten years at Srinagar, J&K was compared with snow areal extents of Indus-S basin.

Table 1. Mean monthly areal extent of snow and snow-line altitude from 2004 to 2014

Basin	Indus-N basin		Indus-S basin		Chenab basin	
Month	Area (STDEV = 8410) (sq. km)	Altitude (STDEV = 370) (m)	Area (STDEV = 8023) (sq. km)	Altitude (STDEV = 435) (m)	Area (STDEV = 4232) (sq. km)	Altitude (STDEV = 783) (m)
October	31,294	4,852	7,606	5,008	6,884	4,576
November	36,626	4,658	13,513	4,661	9,184	4,281
December	42,335	4,448	21,358	4,268	12,905	3,718
January	50,708	4,036	27,843	3,898	16,953	2,802
February	53,225	3,867	29,000	3,820	17,827	2,522
March	51,545	3,982	26,671	3,973	17,118	2,753
April	48,255	4,177	22,092	4,230	15,164	3,257
May	40,443	4,521	16,066	4,531	12,510	3,787
June	32,203	4,817	9,258	4,902	7,467	4,502

Basin	Satluj basin		Ganga basin		Western and West-Central Himalayan region	
Month	Area (STDEV = 3446) (sq. km)	Altitude (STDEV = 664) (m)	Area (STDEV = 2524) (sq. km)	Altitude (STDEV = 662) (m)	Area (STDEV = 31,844) (sq. km)	Altitude (STDEV = 670) (m)
October	5,171	5,040	5,227	4,791	58,146	4,864
November	5,674	5,011	5,671	4,697	75,231	4,601
December	7,974	4,699	6,599	4,488	99,362	4,199
January	12,640	3,788	10,246	3,503	131,128	3,403
February	13,606	3,268	11,262	3,181	138,973	3,116
March	12,881	3,687	10,642	3,380	132,632	3,346
April	10,948	4,294	9,033	3,859	117,427	3,810
May	8,186	4,676	6,839	4,431	92,437	4,322
June	5,199	5,038	4,659	4,905	57,175	4,879

Results and discussions

Around 640 AWiFS scenes for ten years (2004–05 to 2014–15) for October to June, were utilized to generate snow products covering the five basins. Statistics of snow cover area on each dataset was generated. This area was expressed as the percentage of basin area. The snow cover area from each dataset was entered in an excel sheet to generate a trend of the data. The following discussion deals with observations made on the pattern of intra-annual and inter-annual variations in snow cover.

The purpose of comparing intra-annual and inter-annual variations of accumulation and ablation patterns is to understand the response of different basins located in different geomorphological–climatic settings to snow precipitation. Intra-annual and inter-annual variability of snow cover from October of one year to June of consecutive year for each of the five basins is shown in Figure 3. For easy reference of area statistics, the mean monthly area and mean altitude of snow line are presented in Table 1. Thus Figure 3 shows that the variability is more during accumulation than in ablation period. For each basin, a mean curve is generated as shown in Figure 4. It shows variability of snow cover in each month. The vertical bars in this figure show the mean deviation. The mean curve with variability of all the basins has been combined to produce a common curve for Western and West-Central Himalayan basins as shown in this figure. When all the data is combined, it is observed that variability is reduced which gives a regional scenario of snow cover. In this figure we find that Ganga basin has a gentle slope of accumulation and ablation pattern than steep slopes of Chenab and Satluj basins. This is due to the difference in snow cover among these basins. Referring to Table 1, it is observed that the amount of snow cover varies from one basin to another. One reason for this variability is area-altitude distribution of the basins. This distribution, shown in hypsographic curves in Figure 5, suggests that most of the area of Ganga basin is located at lower altitudes, Indus-S and Chenab basins at middle altitudes and Indus-N and Satluj basins at higher altitudes. Ganga basin receives relatively less snow precipitation in winter during north-western disturbances in comparison to Western Himalaya. The magnitude of maximum snow cover is relatively low in Ganga basin compared to Western and West-Central basins. This could be due to less snowfall received during westerlies and 60% area of this basin falls below 4000 m amsl as shown in Figure 5. However, the magnitude of maximum snow cover area remains almost similar for Western basins. This is an important observation as it indicates similar pattern of snow accumulation and ablation in Western and West-Central

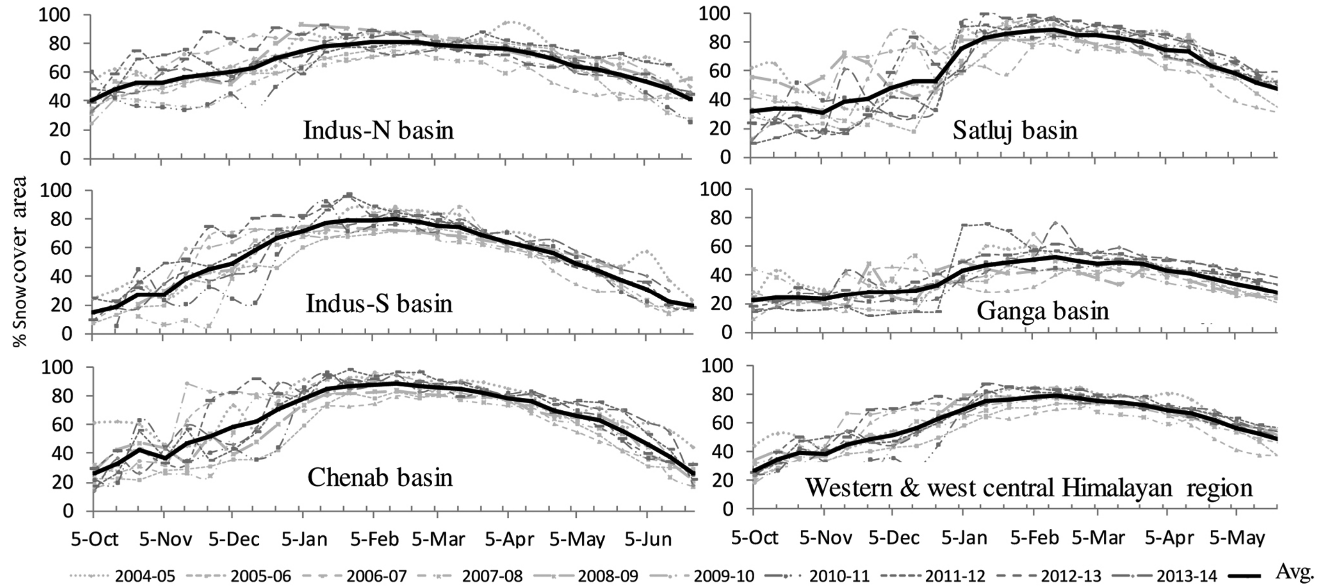

Figure 3. Snow accumulation and ablation pattern between 2004 and 2014.

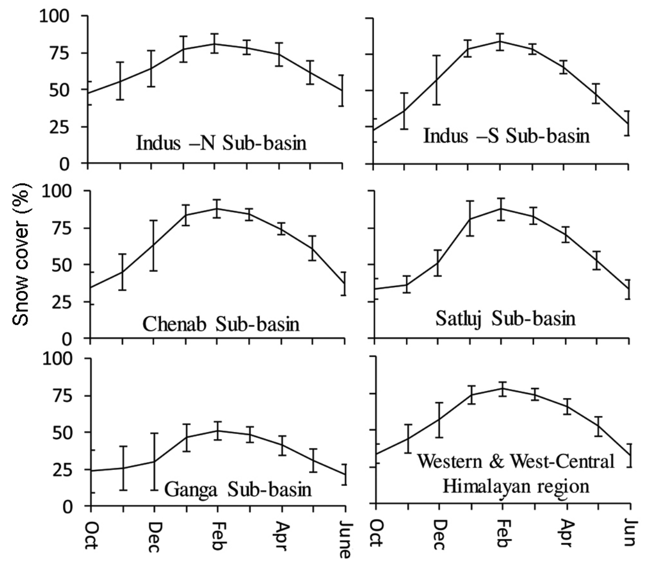

Figure 4. Mean monthly snow cover between 2004 and 2014 along with ± 1σ. Vertical bars show variability.

Himalayan region. Snow precipitation in a basin is a function of altitude, water budget of the clouds, morphological aspects, temperature profiles, wind speed, direction, etc. Similarity or dissimilarity of snow cover patterns cannot be attributed to only one factor[22–29]. These curves were also used to estimate the altitude of snow line based on snow cover extent. This difference of occurrence of basin area in different altitude zones is reflected in the variations of snow accumulation pattern.

Basin-wise trends of snow cover between 2004 and 2014 are expressed in Figure 6. The trends show an increase in snow cover varying from 2% to 7%. Based on Mann–Kendall test, the trends appear insignificant over this period. However, the snow cover trends of all the basins look similar. This indicates a similar snow cover pattern in Western and West-Central Himalaya basins. These trends also indicate that the minor increase in snow precipitation over the years is uniform in the Western and West-Central Himalayan region. For the geomorphological control of the basins on precipitation, the trends indicate a steady condition over the entire Western and West-Central Himalayan region. Though this ten-years period is too small to establish a climatic trend, it perhaps helps in monitoring of snow at shorter intervals which could be later integrated for a long-term understanding of the climate. All individual snow cover trends are combined to produce a single trend for all basins which is useful to observe a regional scenario of snow cover whereas the individual trends can be used to understand at the basin level.

The minimum (Figure 7) and maximum (Figure 8) snow cover of each year for each basin was also analysed. This analysis is useful to understand the extreme conditions of climatic control over snow cover. A significant observation has come out after analysing this data. A subtle decreasing trend of minimum snow cover and an increasing trend in maximum snow cover were observed in Satluj basin. This shows that snow reaches lower altitudes during winter and higher altitudes during ablation season especially in Satluj basin. There is not much variation in minimum snow cover but there is large variation in maximum snow cover, especially in Ganga basin with 12% increase and in Satluj basin with 20% increase in trend from 2004 to 2014. The decreasing trend of minimum snow cover may lead to negative mass balance of glaciers of Satluj basin.

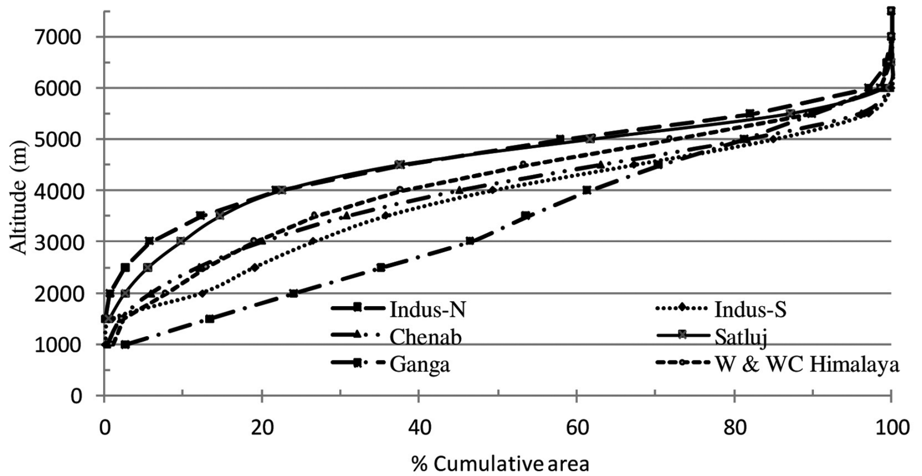

Figure 5. Hypsographic curve giving percentage cumulative area for all five basins and Western and West-Central Himalayan region.

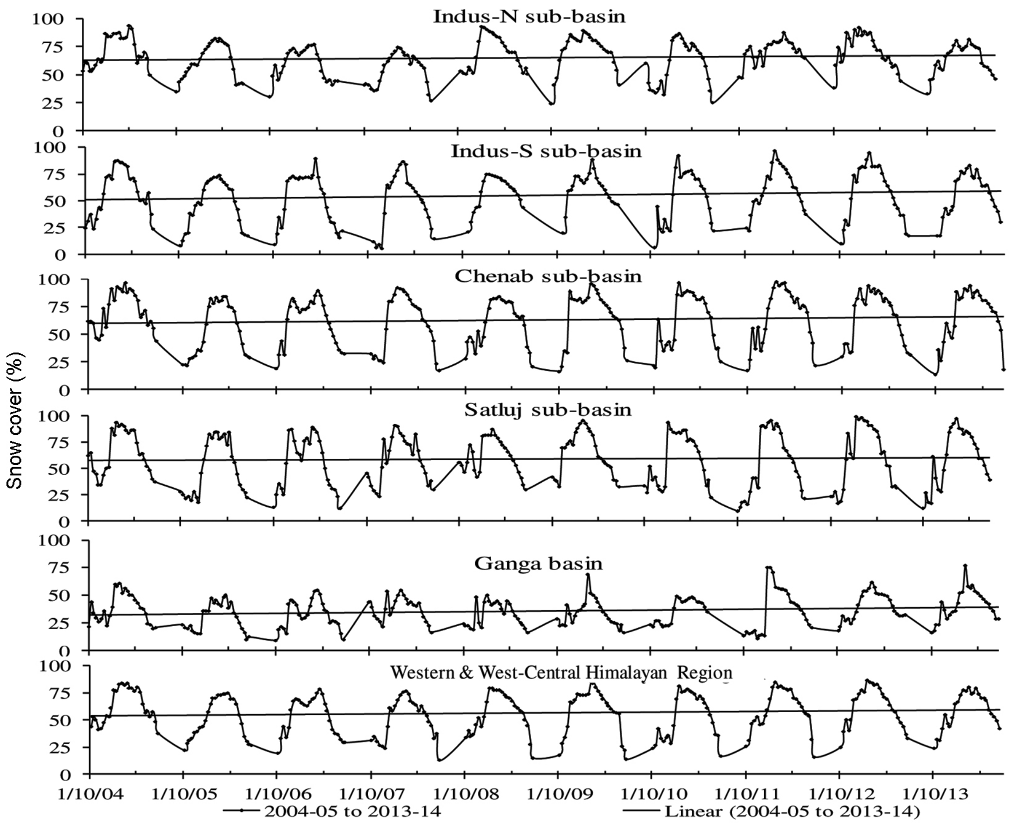

Figure 6. Variation in snow cover areal extent at basin scale and for Western and West-Central Himalayan region. Black straight line shows the trend in variation of snow cover areal extent from 2004 to 2014.

The snow cover was also correlated with available temperature data ruling out the influence of other factors. Temperature data of Srinagar from 2004 to 2014 is shown in Figure 9 which shows that there is no significant increase or decrease in maximum and minimum temperatures. This also supports little or no change in snow cover data. Snow cover and temperature variations as shown simultaneously in Figure 10 clearly indicate the effect of temperature on snow cover variability. It also shows that as temperature increases, snow cover decreases but 97% of the area remains covered with snow even at 17°C. Though, there is snow cover thinning due to melting, it is not however reflected in the loss in area, as there is always a time lag between the effect of temperature on the two processes of accumulation and ablation.

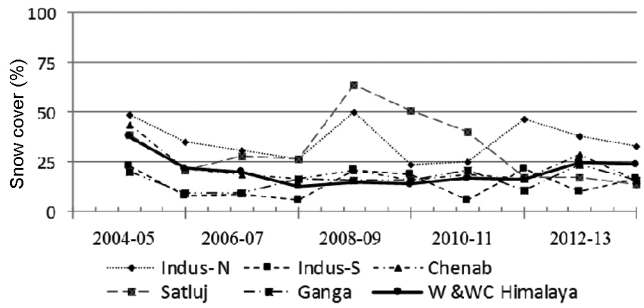

Figure 7. Variation in annual minimum snow cover trend from 2004 to 2014 (October to June).

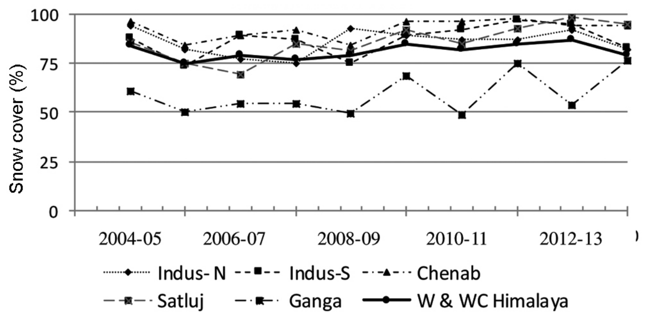

Figure 8. Variation in annual maximum snow cover trend from 2004 to 2014 (October to June).

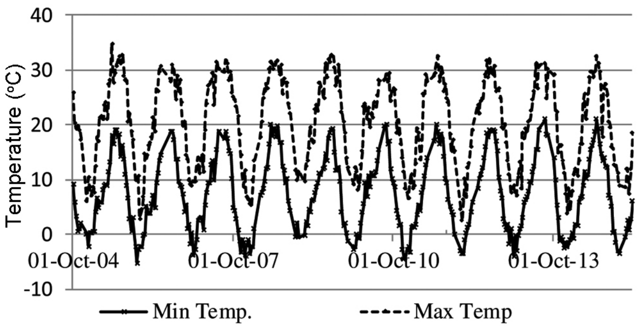

Figure 9. Air temperature (daily 10 on an average) at Srinagar (Jhelum sub-basin part of Indus-S basin) showing no significant increasing or decreasing trend in the air temperature (source: TuTiempo.net).

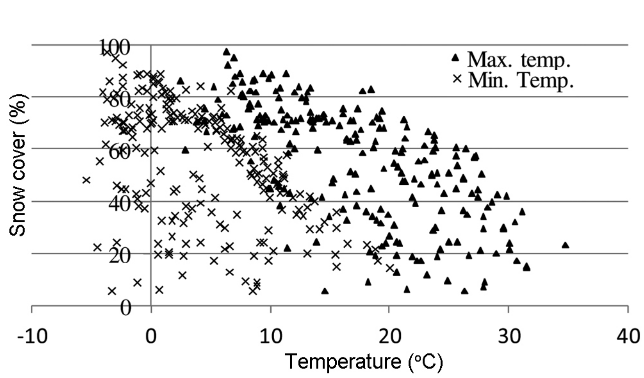

Figure 10. Scatter plot of snow cover of Indus-S basin and air temperature data (at Srinagar) indicating good inverse correlation of air temperature with snow cover.

Overall, these datasets and analysis are vital for climate policy makers. These datasets will be highly useful in future when trends of a longer period will be realized through more and more use of satellite data in snow cover mapping. The snow cover products can be utilized by hydrologists in developing suitable model for melt-runoff estimation and in monitoring of snow fed lakes.

1. Hall, D. K., Riggs, G. A. and Salomonson, V. V., Development of methods for mapping global snow cover using moderate resolution Image Spectroradiometer data. *Remote Sensing Environ.*, 1995, **54**, 127–140.
2. Pepe, M., Brivio, P. A., Rampini, A., Rota Nodari, F. and Boschetti, M., Snow cover monitoring in Alpine regions using ENVISAT optical data. *Int. J. Remote Sensing*, 2005, **26**, 4661–4667.
3. Lemke, P. *et al.*, Observations: changes in Snow, ice and frozen ground. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Solomon, S. *et al.*), Cambridge University Press, Cambridge and New York, 2007, pp. 337–384.
4. Wiscombe, N. J. and Warren, G. S., A model for spectral albedo of snow, I, pure snow. *J. Atmos. Sci.*, 1981, **37**, 2712–2733.
5. Groisman, P. Y., Karl, T. R. and Knight, R. W., Observed impact of snow cover on the heat balance and the rise of continental spring temperatures. *Science*, 1994, **263**, 198–200.
6. Groisman, P. Y., Karl, T. R. and Knight, R. W., Changes of snow cover, temperature and relative heat balance over the Northern hemisphere. *J. Climatol.*, 1994, **7**, 1633–1656.
7. Foster, J. L. and Chang, A. T. C., Snow cover. In *Atlas of Satellite Observations Related to Global Change* (eds Gurney, R. J., Parkinson, C. L. and Foster, J. L.), Cambridge University Press, Cambridge, 1993, pp. 361–370.
8. Klein, A. G., Hall, D. K. and Nolin, A. W., Development of a prototype snow albedo algorithm for the NASA MODIS instrument. In 57th Eastern Snow Conference, 17–19 May 2000, Syracuse, NY, 2000, pp. 143–158.
9. Jain, S. K., Goswami, A. and Saraf, A. K., Accuracy assessment of MODIS, NOAA and IRS data in snow cover mapping under Himalayan conditions. *Int. J. Remote Sensing*, 2008, **29**, 5863–5878.
10. Zhao, H. and Fernandes, R., Daily snow cover estimation from advanced very high resolution radiometer polar pathfinder data over northern hemisphere land surfaces during 1982–2004. *J. Geophys. Res.*, 2009, **114**, 1–14.
11. Akyurek, Z. and Sorman, A. U., Monitoring snow-covered areas using NOAAAVHRR data in the eastern part of Turkey. *Hydrol. Sci.*, 2002, **47**, 243–252.
12. Kulkarni, A. V., Mathur, P., Rathore, B. P., Alex, S., Thakur, N., and Kumar, M., Effect of global warming on snow ablation pattern in the Himalayas. *Curr. Sci.*, 2002, **83**(2), 120–123.
13. Rathore, B. P. *et al.*, Spatio-temporal variability of snow cover in Alaknanda, Bhagirathi and Yamuna sub-basins, Uttarakhand Himalaya. *Curr. Sci.*, 2015, **108**(7), 1375–1380.
14. Kulkarni, A. V., Rathore B. P., Singh, S. K. and Ajai, Distribution of seasonal snow cover in central and western Himalaya. *Ann. Glaciol.*, 2010, **51**(54), 123–128.
15. Singh, S. K., Rathore, B. P., Bahuguna, I. M. and Ajai, Snow cover variability in the Himalayan-Tibetan region. *Int. J. Climatol.*, 2013, **34**, 446–452; doi:10.1002/joc.3697.
16. Rathore B. P., Kulkarni, A. V. and Sherasia, N. K., Understanding future changes in snow and glacier melt runoff due to global warming in Wangar gad sub-basin, India. *Curr. Sci.*, 2009, **97**(7), 1077–1081.
17. Agarwal, K. G., Kumar, V. and Das, T., Melt runoff for a sub-basin of Beas sub-basin. In Proceedings of the First National

Symposium on Seasonal Snow Cover, New Delhi, 28–30 April 1983, p. 43.
18. Jain, S. K., Goswami, A. and Saraf, A. K., Snowmelt runoff modeling in a Himalayan basin with the aid of satellite data. *Int. J. Remote Sensing*, 2010, **31**(24), 6603–6618.
19. Kulkarni, A. V., Singh, S. K., Mathur, P. and Mishra, V. D., Algorithm to monitor snow cover using AWiFS data of RESOURCESAT for the Himalayan region. *Int. J. Remote Sensing*, 2006, **27**(12), 2449–2457.
20. Markham, A. L. and Barker, J. L., Thematic Mapper bandpass solar exoatmospheric irradiances. *Int. J. Remote Sensing*, 1987, **8**(3), 517–523.
21. Rubus, B. M., Eineder, M., Roth, A. and Bamler, R., The shuttle radar topography mission a new class of digital elevation models acquired by Space borne radar. *ISPRS J. Photogramm. Remote Sensing*, 2003, **57**(4), 241–261.
22. Elder, K., Dozier, J. and Michaelsen, J., Snow accumulation and distribution in an alpine watershed. *Water Resour. Res.*, 1991, **27**, 1541–1552.
23. Fohn, P. and Meister, R., Distribution of snow drifts on ridge slope: measurements and theoretical approximations. *Ann. Glaciol.*, 1983, **4**, 52–57.
24. Grünewald, T., Schirmer, M., Mott, R. and Lehning, M., Spatial and temporal variability of snow depth and ablation rates in a small mountain catchment. *The Cryosphere*, 2010, **4**, 215–225; doi:10.5194/tc-4-215-2010.
25. Lehning, M., Lowe, H., Ryser, M. and Raderschall, N., Inhomogeneous precipitation distribution and snow transport in steep terrain. *Water Resour. Res.*, 2008, **44**, W07404; doi:10.1029/2007WR006545.
26. Luce, C., Tarboton, D. and Cooley, K., The influence of the spatial distribution of snow on basin-averaged snowmelt. *Hydrol. Process.*, 1998, **12**, 1671–1683.
27. Mott, R., Schirmer, M., Bavay, M., Grunewald, T. and Lehning, M., Understanding snow-transport processes shaping the mountain snow-cover. *Cryosphere*, 2010, **4**, 545–559; doi:10.5194/tc-4-545-2010.
28. Raderschall, N., Lehning, M. and Schär, C., Fine scale modeling of the boundary layer wind field over steep topography. *Water Resour. Res*., 2008, **44**, W09425; doi:10.1029/2007WR006544.
29. Winstral, A., Elder, K. and Davis, R., Spatial snow modelling of wind-redistributed snow using terrain-based parameters. *J. Hydrometeorol*., 2002, **3**, 524–538.

ACKNOWLEDGEMENTS. We are grateful to Dr Tapan Misra, Director, Space Applications Centre, ISRO, Ahmedabad for overall support. We also thank Dr Raj Kumar, Deputy Director, EPSA/SAC, Ahmedabad and Dr Anil Kulkarni, Distinguished Scientist, Divecha Centre of Climate Change, IISc, Bengaluru for valuable support and encouragement.

doi: 10.18520/cs/v114/i04/800-807